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Title: Megafires: A New Fire Paradigm

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Megafires: A New Fire Paradigm

Presenter: Jon Reisner

Presentation for XCP Division:

November 18, 2021

”Brief” History of LANL Wildfire Effort

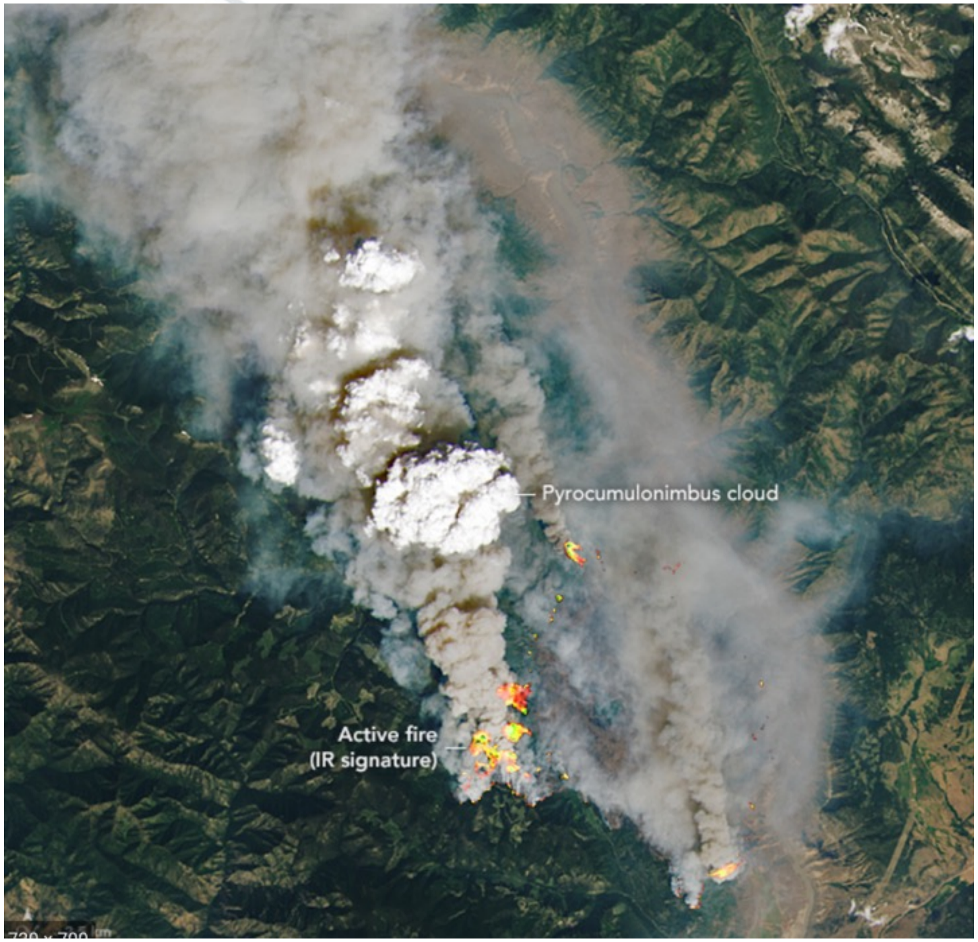
- 25 years ago started a wildfire modeling effort with Rodman Linn to help educate firefighters…
  - Due to the South Canyon Fire near Glenwood Springs Colorado that killed 14 wildland firefighters
  - And a fire in Calabasas California that killed an urban firefighter
  - Also, good problem to test limits of high performance computing
- This work led to the development of HIGRAD-FIRETEC that has been used to examine a range of fires, controlled burns, and forest management
- Rodman Linn and Mike Brown have recently developed QUIC-FIRE for DoD applications and wildland firefighters
- HIGRAD-FIRETEC is currently being used to examine a variety of large fires including megafires

South Canyon Fire July 6 1994
2000 acre fire (small by current standards)

Megafires: A New "Normal" in Wildfires

Los Alamos NATIONAL LABORATORY EST.1943

- Rough definition: a fire >100,000 acres
- Fires of this size can burn for months and during runs can…
  - Produce multiple pyrocumulonimbus (pryoCbs) and lightning…
  - Starting more fires including peatmoss
  - And inject a large number of aerosols into the stratosphere, 2-3 orders above background (*climate impact*)
  - Impact weather, visibility and health (*worse than diesel smoke*)
- Rough analog to fires produced after a nuclear detonation



Active fires and pyroCb in Siberia

Latest Headline Concerning Global Fire Activity

Here Are the 6 Major Regions Literally on Fire Right Now

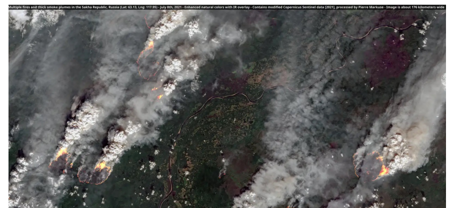
A shocking amount of wildfires are burning around the northern hemisphere as the summer from hell rages on.

3rian Kahn | Thursday 5:30PM | Comments (5) | Alerts

California

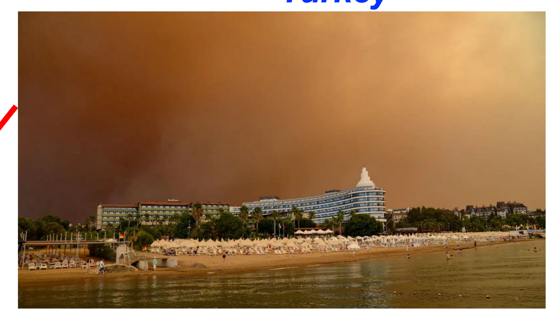
Manitoba

Siberia



Finland

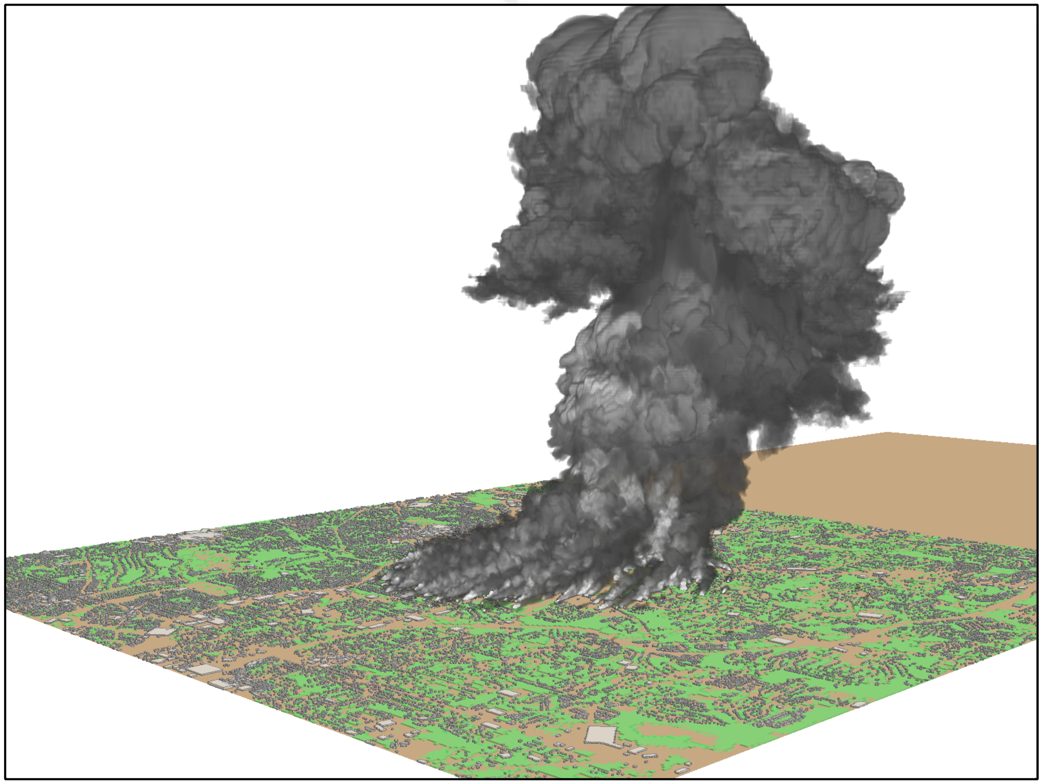
Turkey



Sardinia

Megafires: Analog to Nuclear Airburst Induced Fires

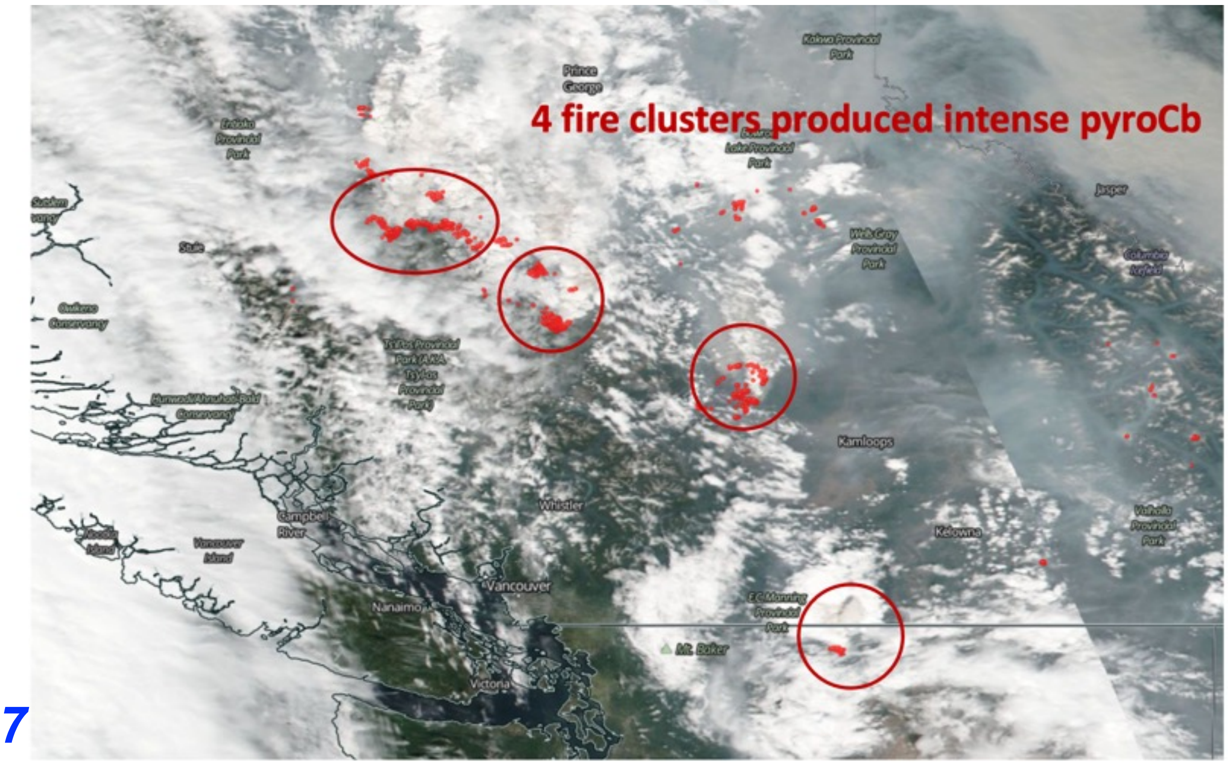
- Hiroshima airburst produced a firestorm…extremely complex fire/fallout problem
- Firestorms and/or fires induced by a nuclear detonation…
  - can inject black carbon or soot into the stratosphere
  - Soot induces cooling
  - And possible crop failures
- LANL is demonstrating that nuclear winter impacts appear to be less than previously suggested
- The 2017 British Columbia fire (BC17) was equivalent in acreage to 100 15kt detonations
- BC17 produced only 0.04 Tg of soot…5 Tg was assumed by the nuclear winter community



Smoke from fires induced by a 15 kt detonation over Atlanta

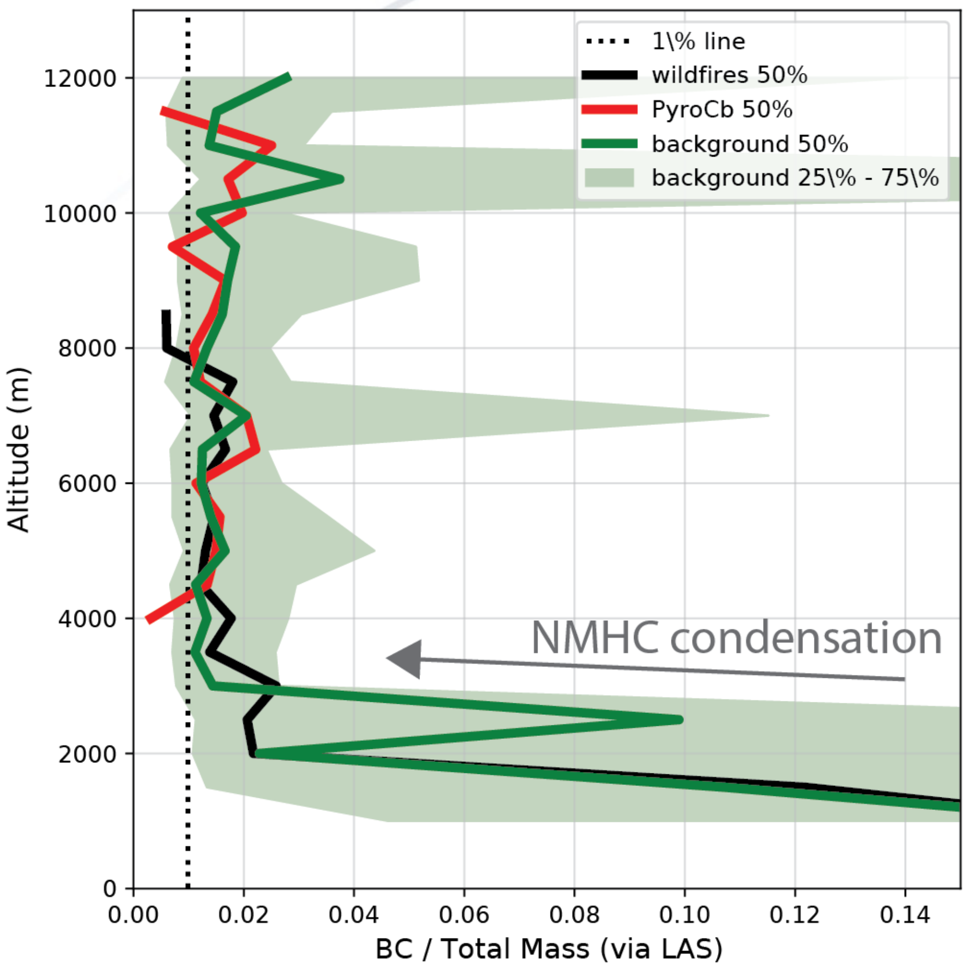
BC17 Megafire: An Example of a Significant Upper Atmospheric Injection

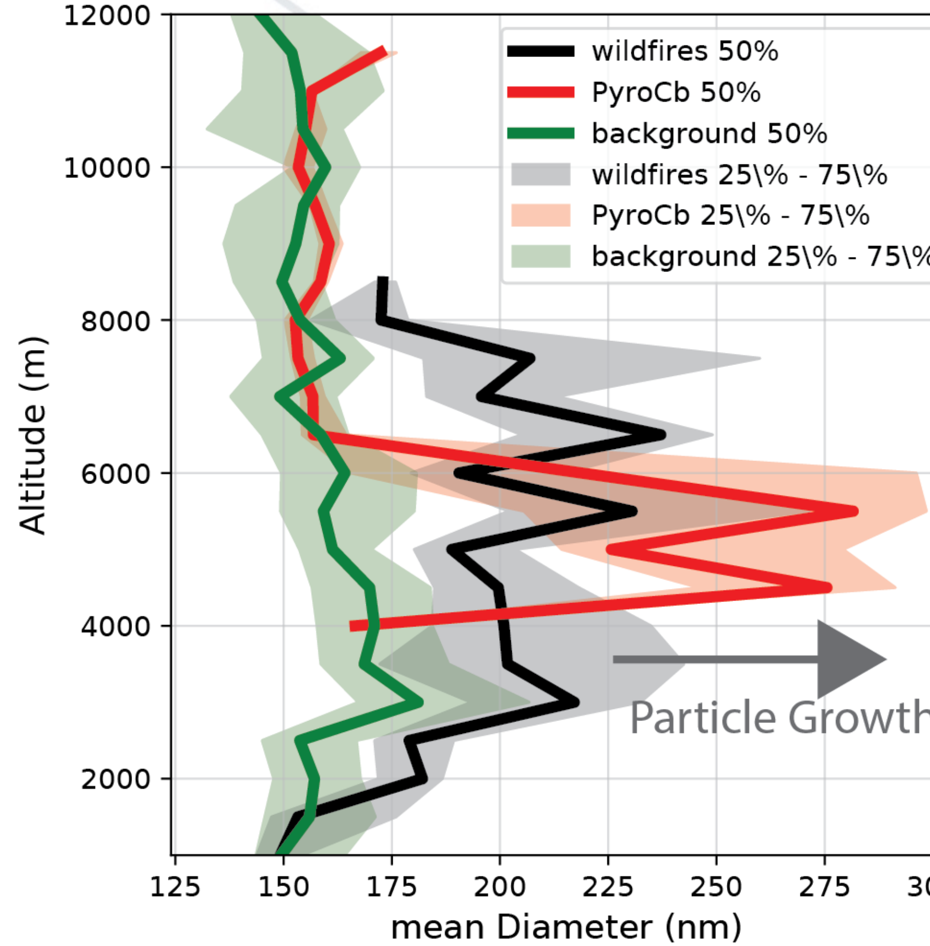
- Multiple pyroCbs
- 0.1-0.3 Teragrams (Tg) of aerosol injected into the upper atmosphere
  - Soot (2%) too low from current wildland fuel loading and emission factors
- Informed multi-scale modeling
  - Detailed combustion modeling
  - Fire physics and pyroCb dynamics at high-resolution
  - High resolution climate modeling



Visible Satellite; 12 August 2017

Where does the soot go?





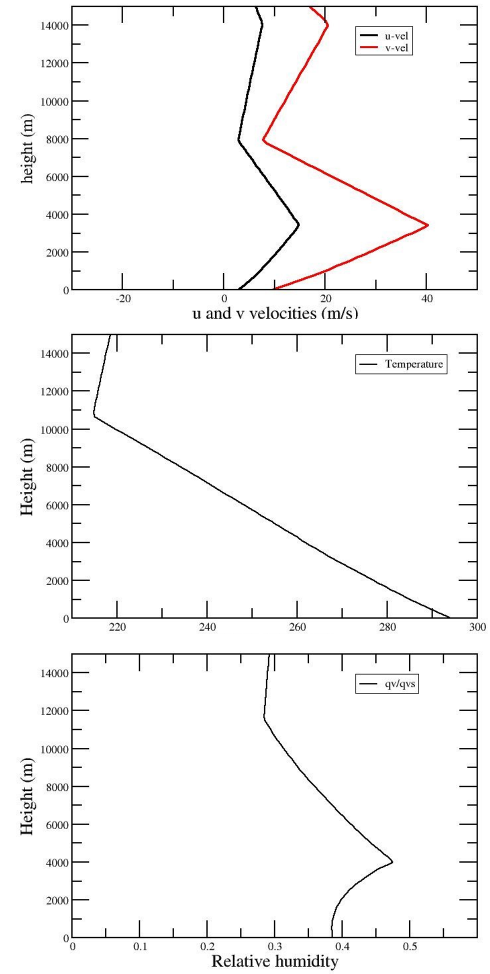
FIREX data from multiple fires; BC17 follows similar trend

Unique Aspects of BC17 Event

Los Alamos NATIONAL LABORATORY EST. 1943

Google Earth image (left) showing impact of logging activity and unique fuel loading pattern from BC17; patches have slash piles (right) left after logging.

Soundings for PyroCb HIGRAD simulations

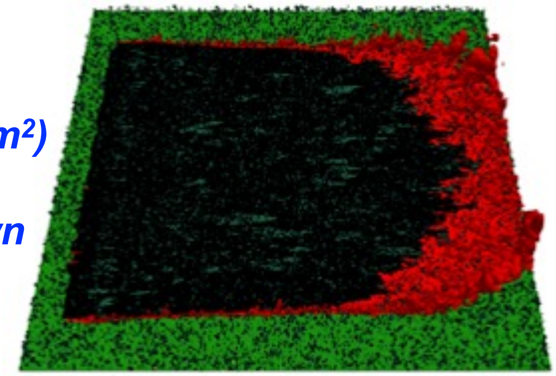


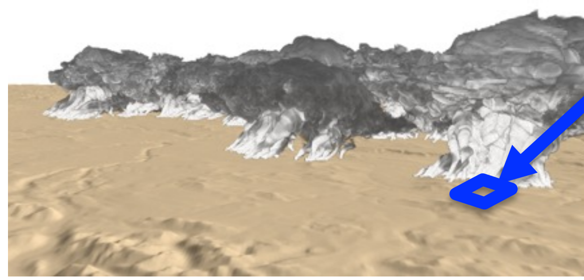
- Mixture of slash pile and forest fuel, due to logging activity and beetle kill
- Slash piles are denser burn slower and longer than the forest
- Relatively high winds ahead of a cold front (conflagration versus firestorm)
- Mid-level moisture induces pyroCbs
- Tropopause Observed at ~11 km
- 400,000 acres burning during an afternoon

Overview of Informed Multi-Scale Approach

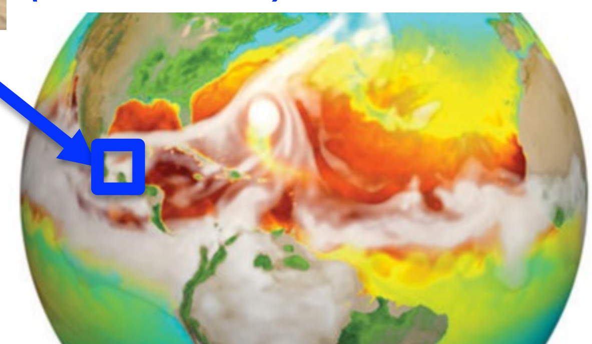
- Three modeling components
  - Fire simulations for fuel types
  - PyroCb simulations with clouds/ice
  - GCM simulations: CESM/GEOS5
- Fire model input drives pyroCb
  - Prognostic heat flux and smoke emissions
- PyroCb input drives GCMs
  - Initial aerosol loading profiles
  - Important for high resolution runs

High-resolution (1x1 km²) HIGRAD-FIRETEC; forest simulation shown





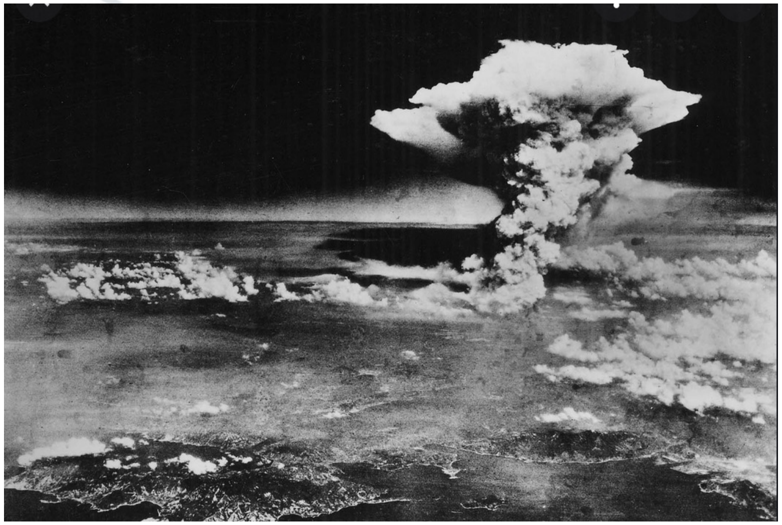
HIGRAD; pyroCb simulation (400x400 km²)

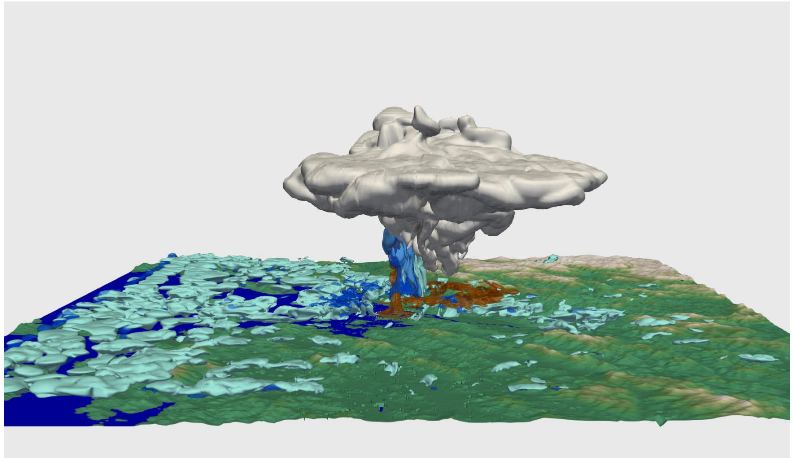


CESM (E3SM) and GEOS-5; Global climate simulations

Overview of HIGRAD: Numerical Formulation Makes Combustion Modeling Possible

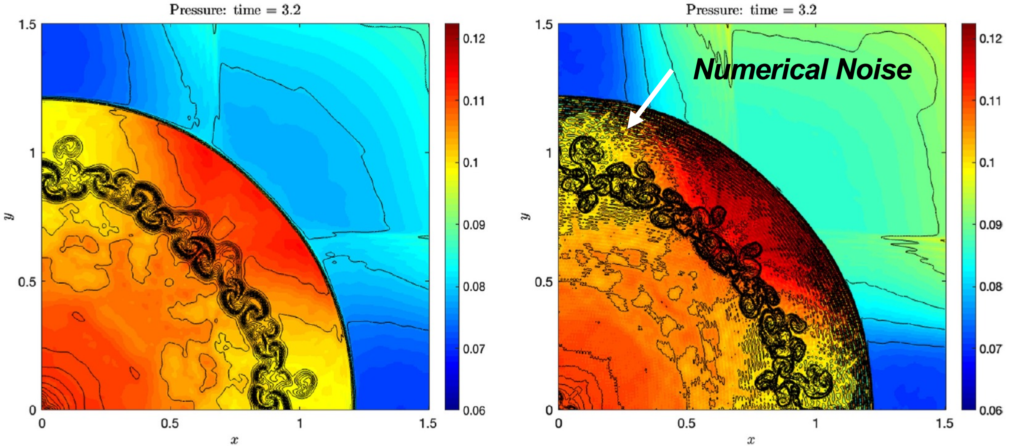
- 25 years of research has led to the development of a numerical solver for the Euler equation set that can accurately model combustion and associated high gradients…
- Current numerical formulation can simulate the evolution of fire fronts or contact surfaces with little generation of numerical instabilities*
- In addition to low Mach number combustion, HIGRAD is also being used to model high Mach number combustion, e.g., shock-fire interaction





HIGRAD Hiroshima simulation

Evolution of Combusting Contact Surface Within a Fireball

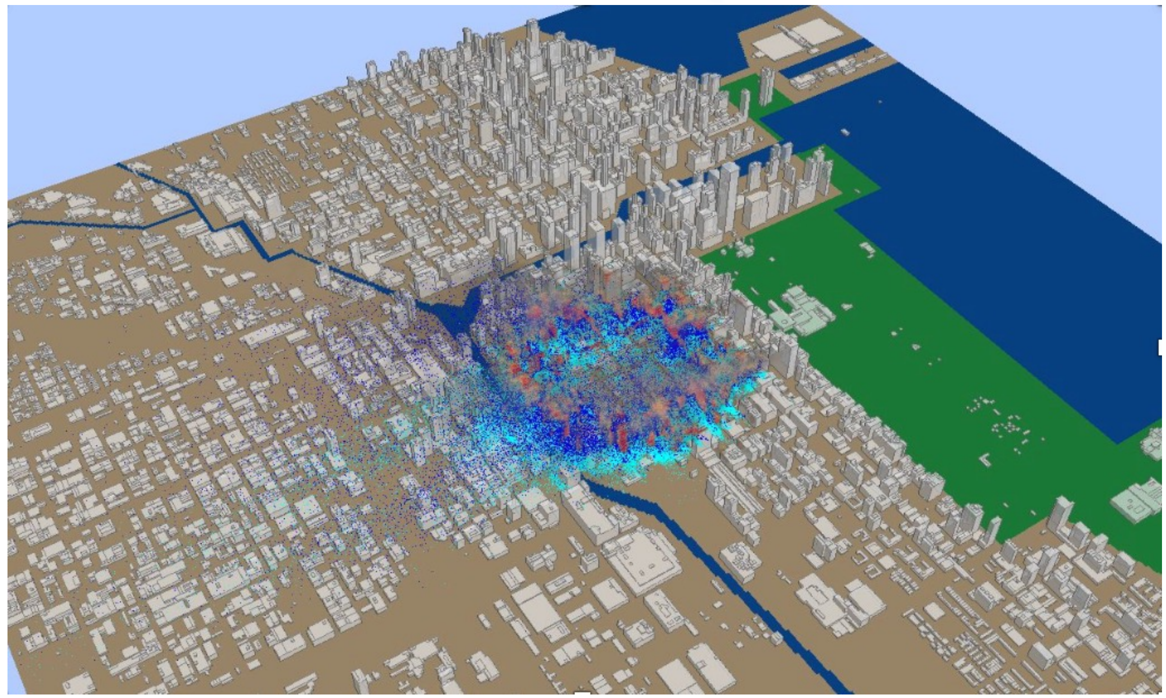


*Ramani, Reisner, & Shkoller, JCP, 2019

Overview of FIRETEC: A First-principle Fire Model

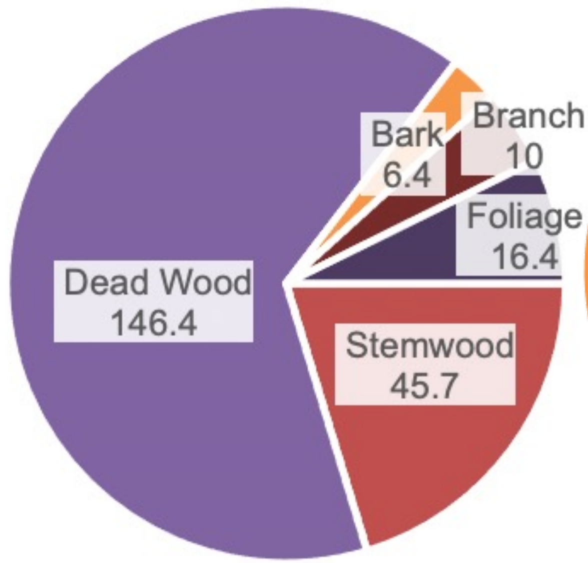
- Represents the "larger-scale" conversion of fuel into gas products
- Represent the fuel temperature & density; as well as a oxygen dependent reaction rate
- Represents both fine and thick fuels
- Thermal Radiation can be included (diffusion or Monte Carlo)
- ***Firebrands also are included…main mechanism for fire spread in a city***
- Detailed chemical kinetics (formation of soot, removes assuming emission factor is 1) and pyro-cumulus formation are being currently tested
- FIRETEC has been reasonably validated against wildland fuels, e.g., grass, trees, shrubs

HIGRAD-FIRETEC Simulation of Chicago with firebrands

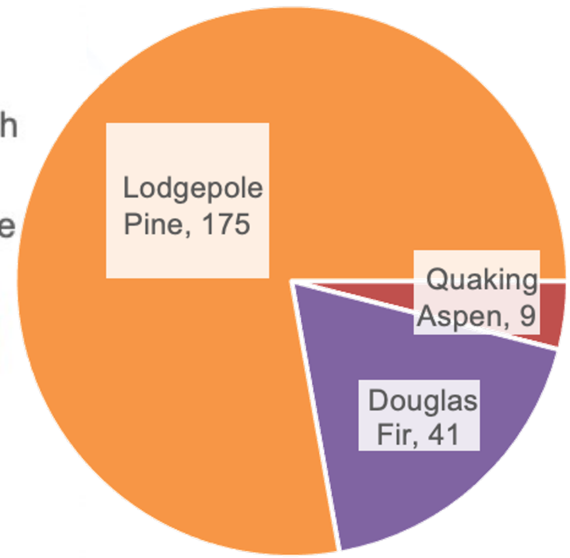


HIGRAD-FIRETEC BC17 Fire Simulations: 1st Component of Informed Multi-Scale Approach

- Canadian FS Observed Fuel Load
  - 65% of dead wood from bark beetle kills
  - Dry fuels from Hot summer
- Forest vs. Slash pile
  - Component fuel loads used
- Winds & humidity: Soundings
- Including smoldering phase of fires
  - Span Active to smoldering phase



Fuel Loading per component (t/ha)



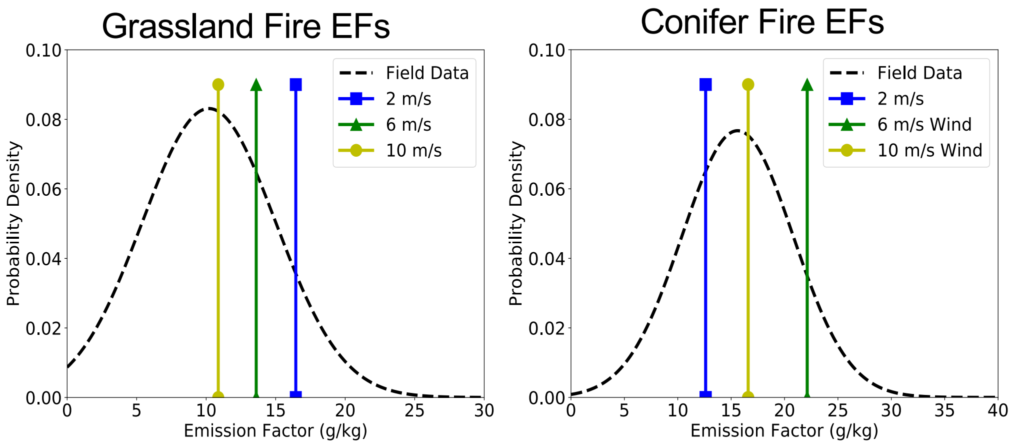
Fuel Loading per species (t/ha)

Zonal-Based Emission Source Term (Z-BEST) Model

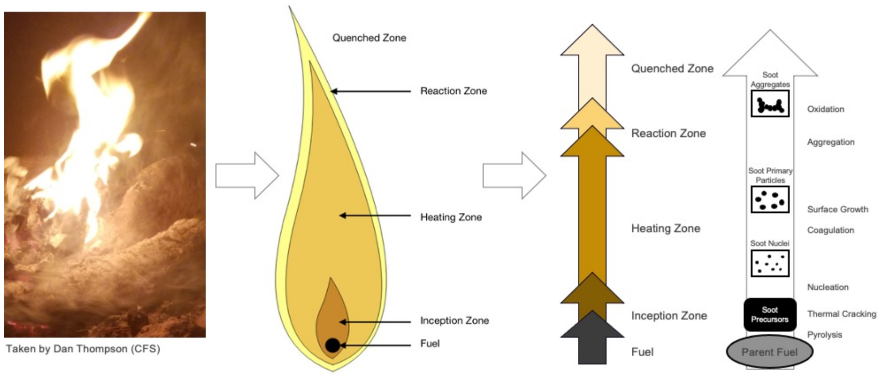
- Z-BEST Aerosol emissions in FIRETEC
- Recreates a flame within a computational cell
- Resolves a particulate formation model along the centerline of reconstructed flame
- Validated emission factors against experimental field measurements

Species	Emission Factor (g/kg) Forest	Emission Factor (g/kg) Slashpile
Flaming $PM_{2.5}$	24	30
Smoldering $PM_{2.5}$	35	40
BC	20%	
OC	80%	

Emission factors in Z-BEST model



Z-BEST model validations with experiments

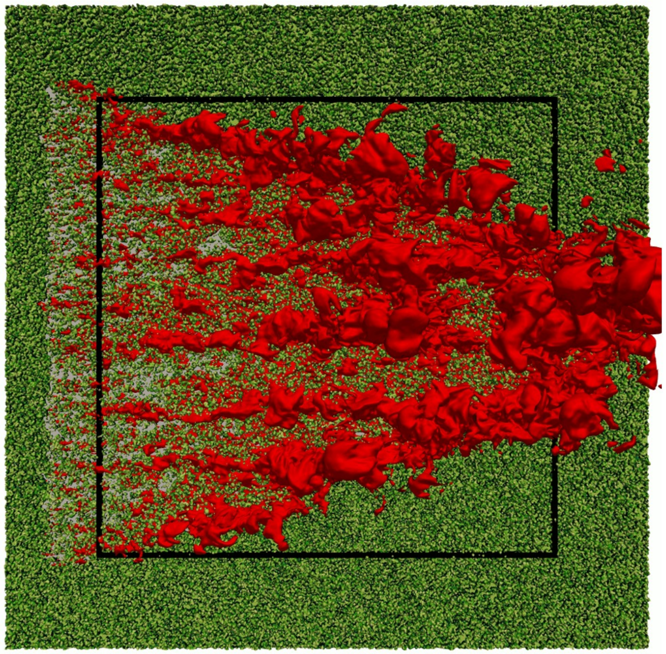


Z-BEST model schematics

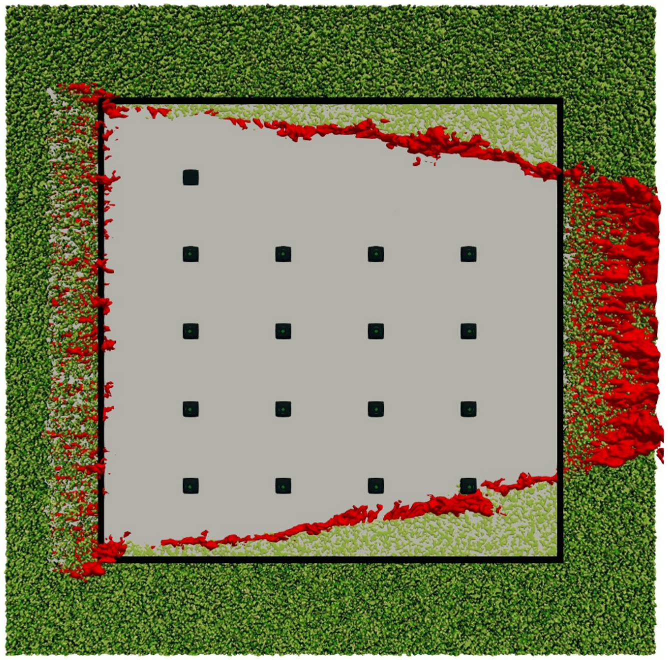
Josephson, et al 2020

HIGRAD-FIRETEC Simulations: Active Burning

Forest



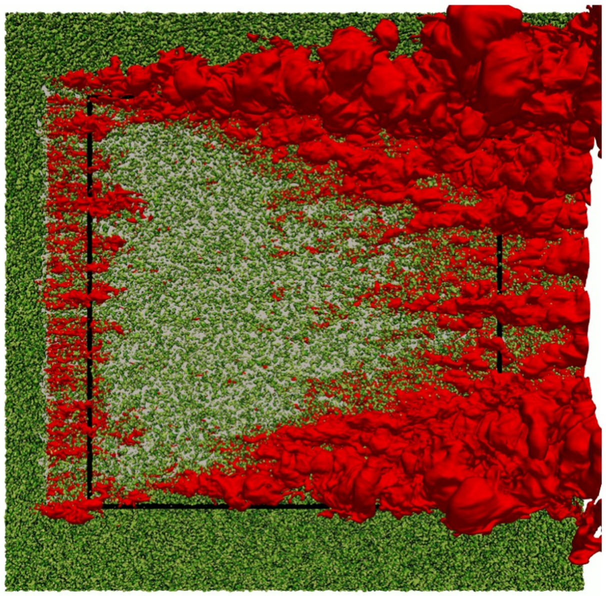
Slash Piles



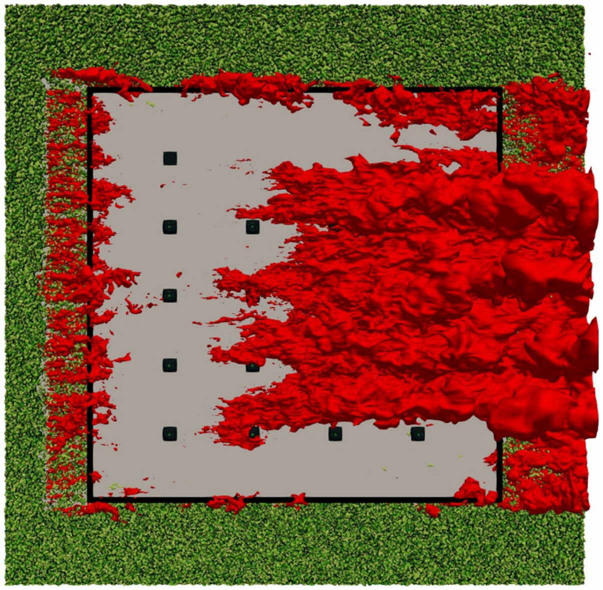
Isosurface of temperature (330 K)

HIGRAD-FIRETEC Simulations: Smoldering

Forest



Slash Piles

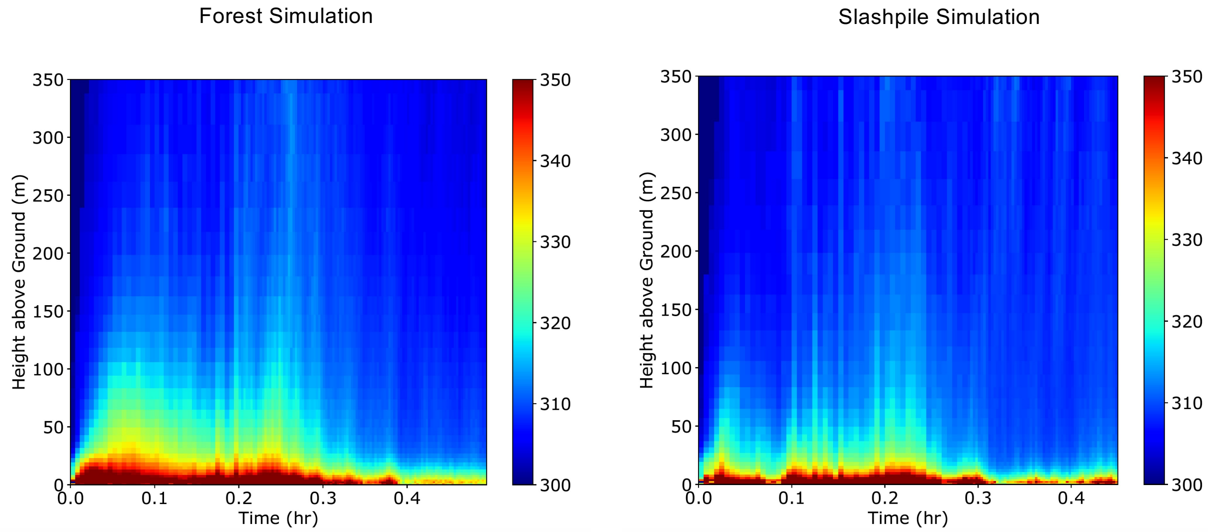


Isosurface of Temperature (305 K)

HIGRAD-FIRETEC: Averaging of Heat Fluxes informing HIGRAD PyroCb Simulations

- ‘Plume’ from FIRETEC simulations
  - Temperature recorded
  - Defined with vertical updraft
- Used for HIGRAD pyroCb simulations
  - At lower heights
  - As ‘forced’ dynamics inputs for energy

Averaged Plume Potential Temperatures



Peak Temp=380 K

Peak Temp=345 K

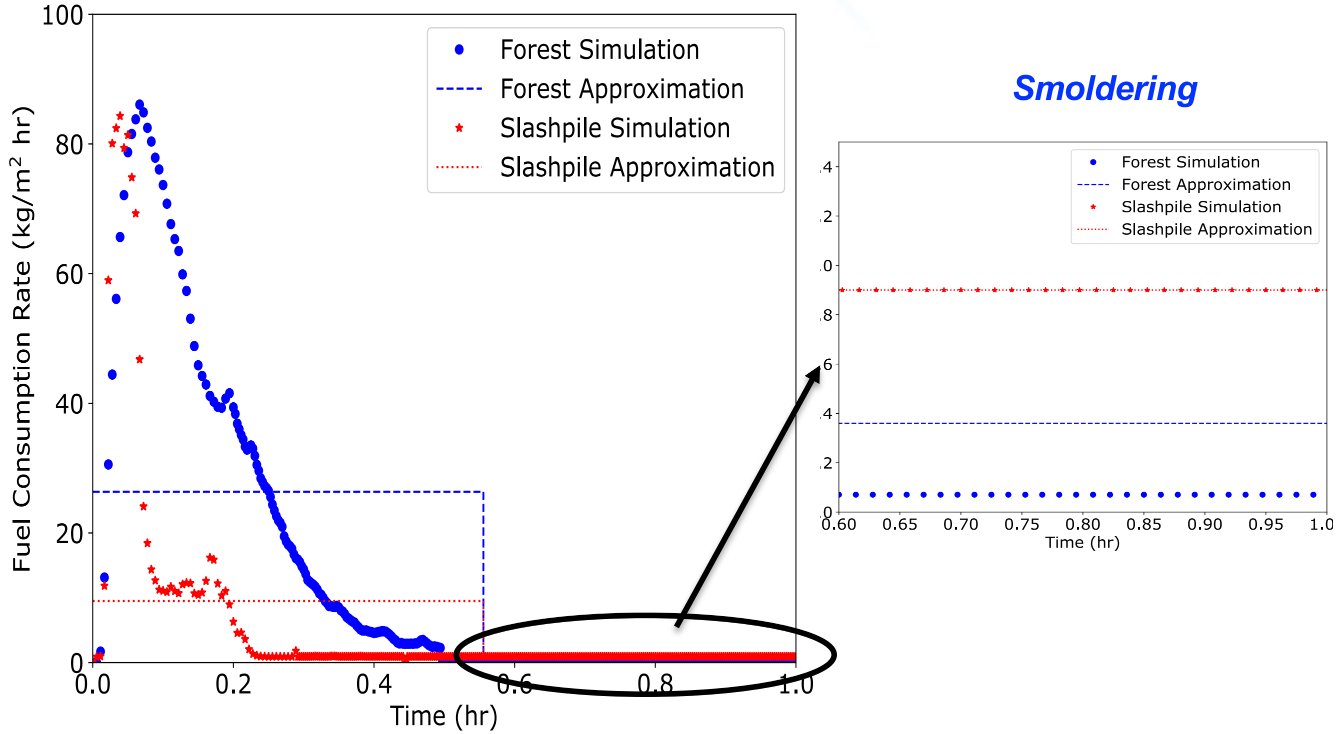
HIGRAD-FIRETEC: Averaging Emissions to inform HIGRAD PyroCb Simulations

- Emissions input for pyroCbs
- Emission factors of species
  - Experiment data (tables)
- Fuel Consumption rates
  - From FIRETEC simulations
  - Active and smoldering phase
  - Averaged over both phases

Gas EFs

Gas Species	Emission Factor (g/kg)
CO_2	1635
CO	90
H_2O	550
O_2	-500
CH_4+others	15

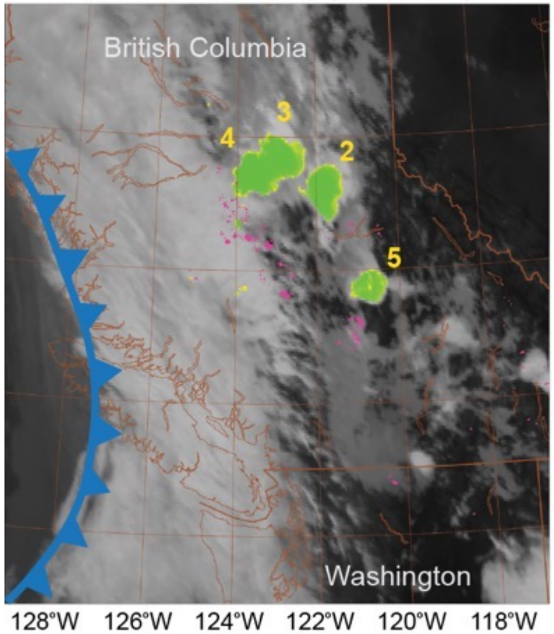
Fuel Consumed (time): Active and smoldering phases



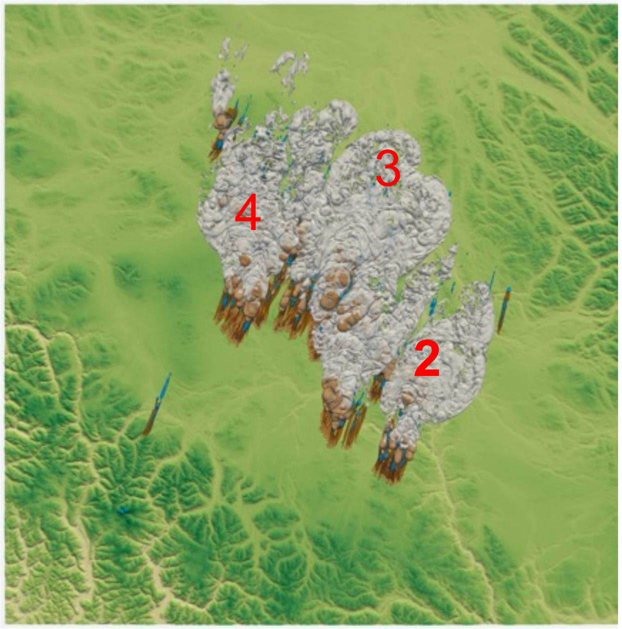
HIGRAD BC17 PyroCb Simulations: 2nd Component of Informed Multi-Scale Approach

- Simulate 3 of 5 observed pyroCbs
  - Satellite hot spot data for 3 pyroCbs used
- 400x400 km^2 domain
- 100m spatial resolution
- Input from FIRETEC
  - Energy (heat) flux
  - Aerosol (organic/soot) emissions; ***3 orders above background***
  - Gas (water vapor/CO) emissions
- Simulations for various fuel setups
  - Forest only
  - Slash only
  - Mixed forest/slash (ground truth)
- Simulations with cloud physics on/off
- Upstream sounding data for initialization

8/13, 01:45 UTC (18:45 LT)



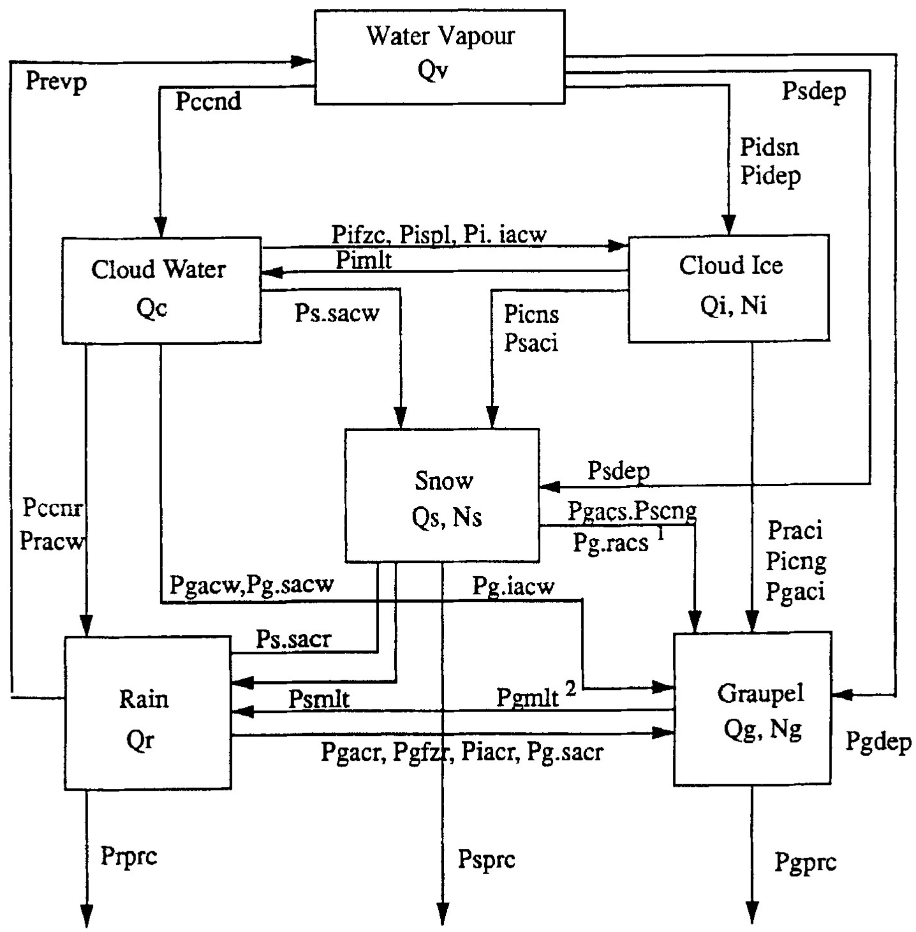
Infrared Satellite Image August 12; strong southerly flow & mid-level moisture ahead of cold front



Cloud ice (white), water (blue), and organic Aerosol (brown) from HIGRAD pyroCb Simulation

Cloud Physics is Complex & Needed for PyroCb Formation

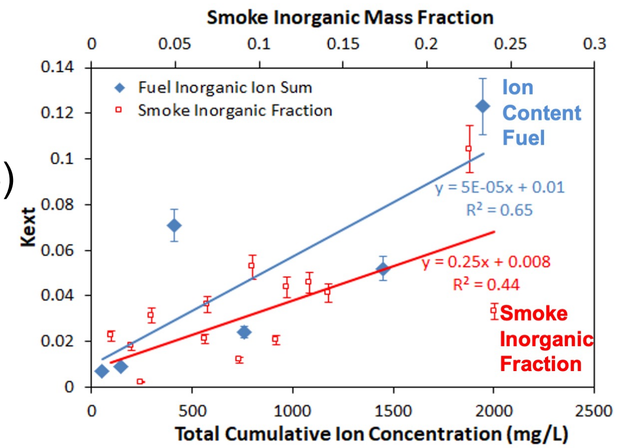
- Cloud physics includes a large number of processes including:
  - Condensation/Evaporation
  - Freezing/Melting
  - Collision/Sweep out
- Bulk approach, distributions are specified
- Scheme has been validated against a range of non-pyroCb
- Modified important processes, condensation and ice activation, based on experimental data…
- Water/ice uptake on soot aerosol is still an open research question



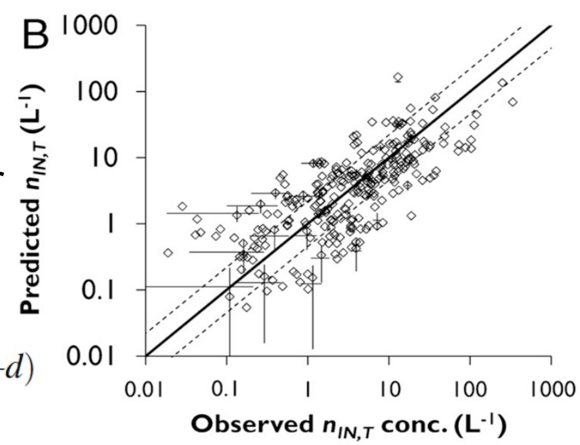
HIGRAD BC17 PyroCb Simulations: Cloud Physics

- Depositional growth of activated ice
  - Latent heat release lofts PyroCb (Reisner '98)
- Ice and water activation
  - Aerosols activated in a Eulerian framework
  - 2 separate size bins for organic and soot
- Water activation and condensation
  - kappa is from literature/CAFÉ (Reisner '09)
- Ice activation parameterization
  - T/size dependence scales with particles larger than 0.5 micron (Demott '10)

$$n_{\mathrm{IN},T_k} = a(273.16 - T_k)^b (n_{\mathrm{aer},0.5})^{(c(273.16-T_k)+d)}$$



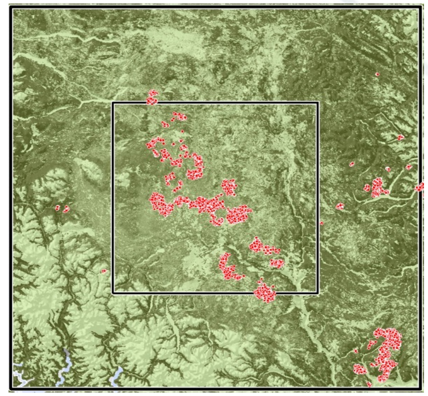
CAFÉ measurements for fire smoke kappa water activation (and enhancement from ions) (Gomez)



Empirical Ice activation parameterization (Demott)

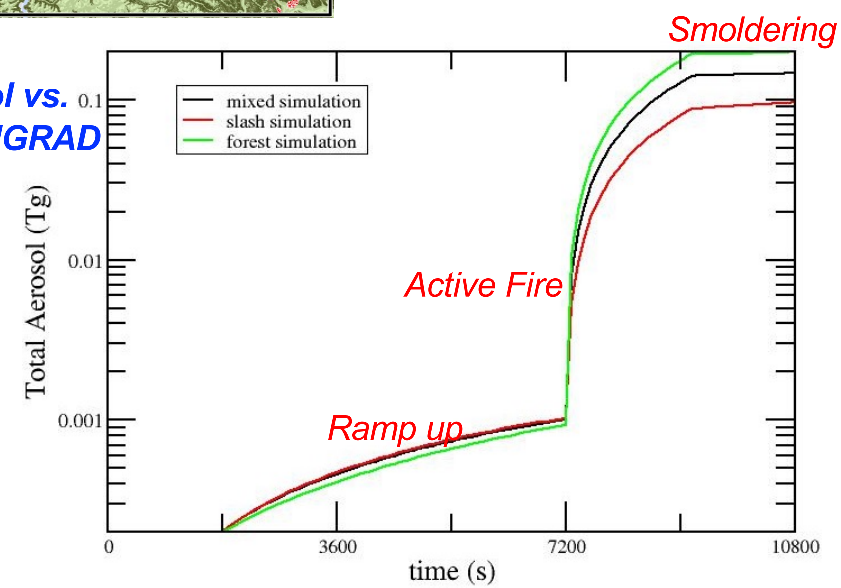
HIGRAD BC17 PyroCb Simulations: Model Setup

- Data from Canadian Forest Service
  - Topography
  - Hot spot data
- Hot spots used as simple mask (0 or 1)
  - Multiplied by source functions
- Mixed forest/slash simulations
  - 2 km^2 patches of forest or slash were specified
  - Treated impact of logging activities
- Three regimes of energy/mass release
  - Ramp up
  - Active fire
  - Smoldering
- Ramp-up phase is important for cloud formation

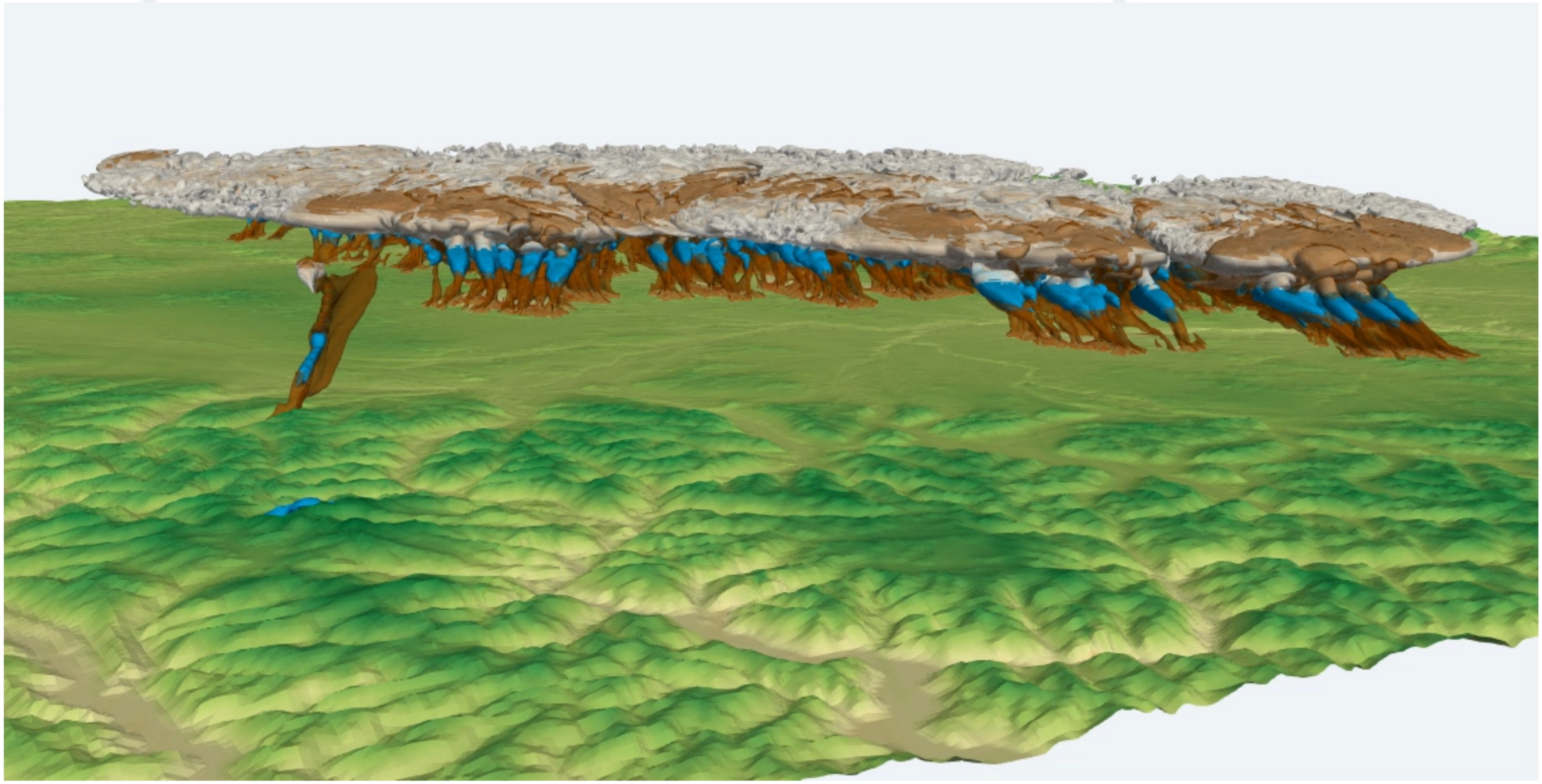


Hot spot data for 400 km x 400 km domain (outer box); Ones in 200 km x 200 km were used in simulations; heat, aerosol, and gases are emitted in hot spots (red patches)

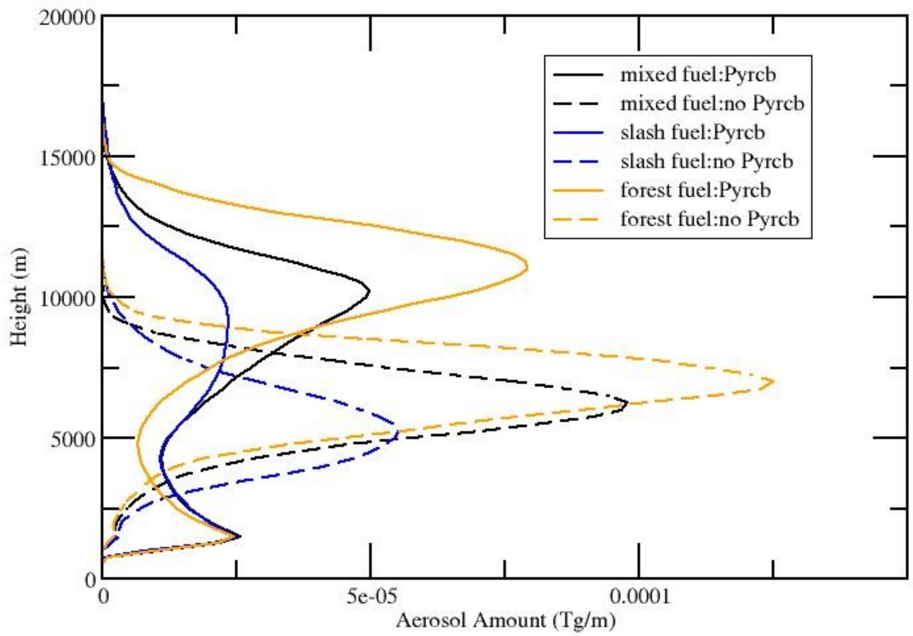
Total aerosol vs. time from HIGRAD simulations

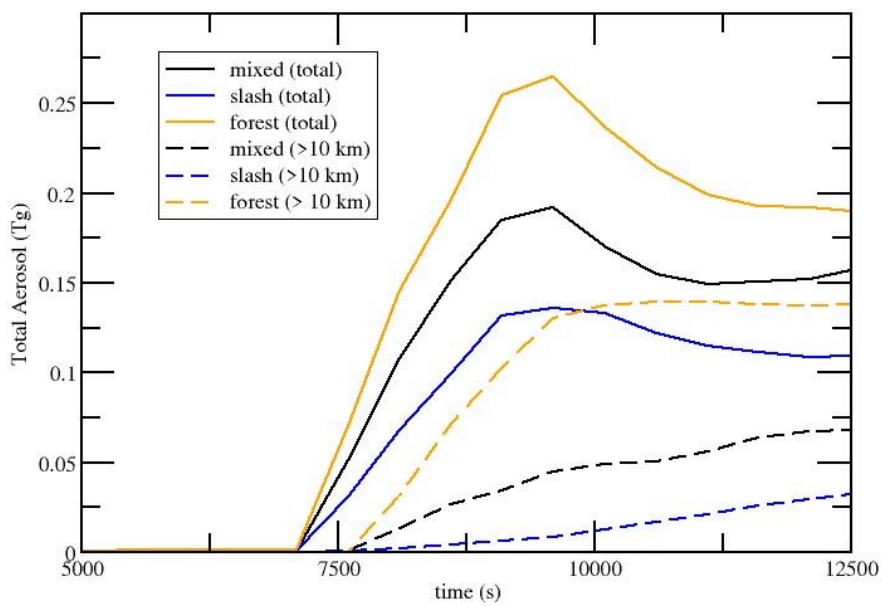


HIGRAD PyroCb Mixed Forest & Slash Simulation



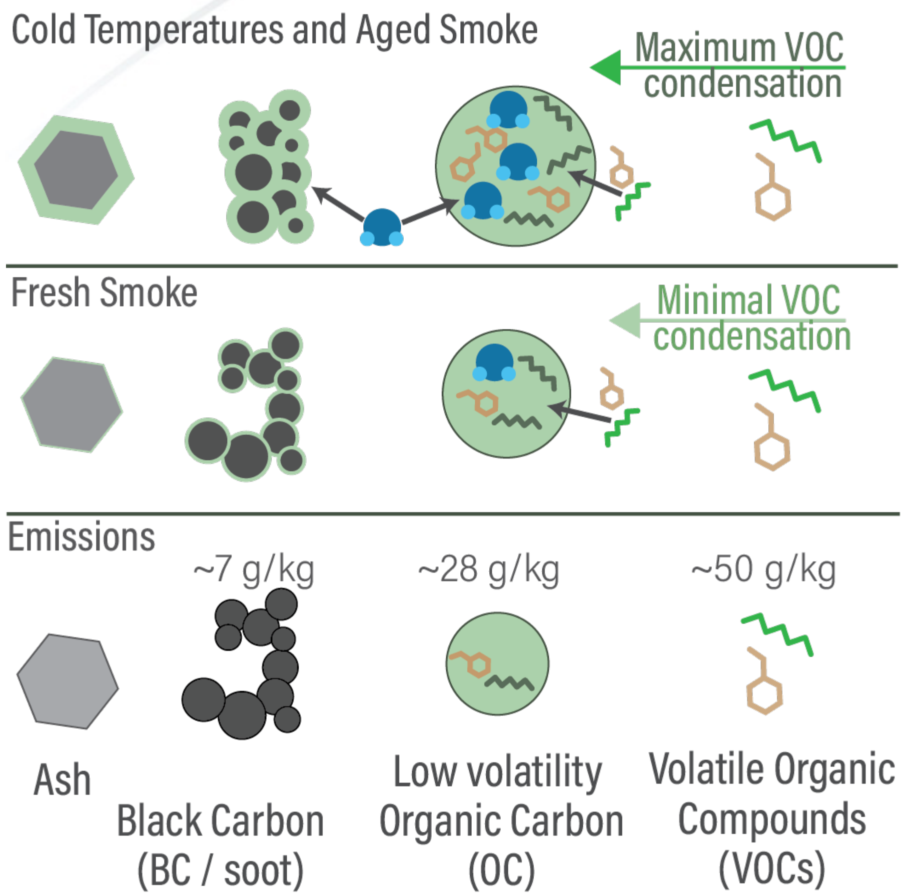
Integrated Aerosol Quantities: Vertical Profiles & Domain Total





Profiles are a function of fuel type

Addition Mass Available from Organic Vapors: Secondary Organic Aerosol

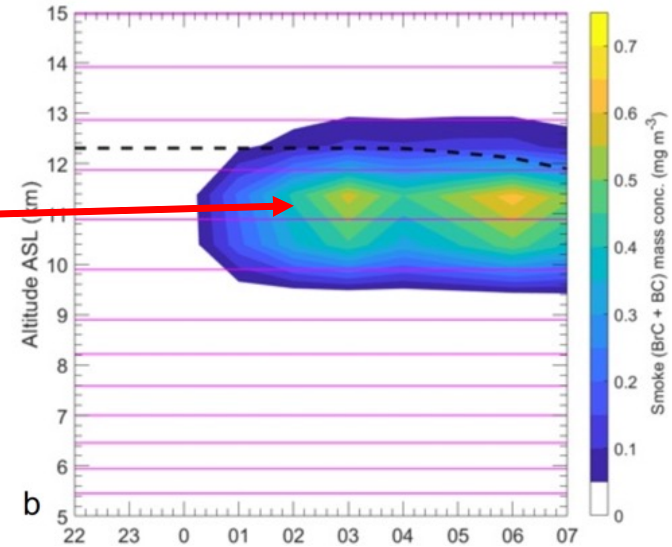


- Volatile organic vapors are co-emitted from fires.
- The vapor pressure of these organics decreases with temperature.
  - Lower vapor pressures drive gas-phase molecules to condense.
- This additional mass helps close the model vs. observation gap.

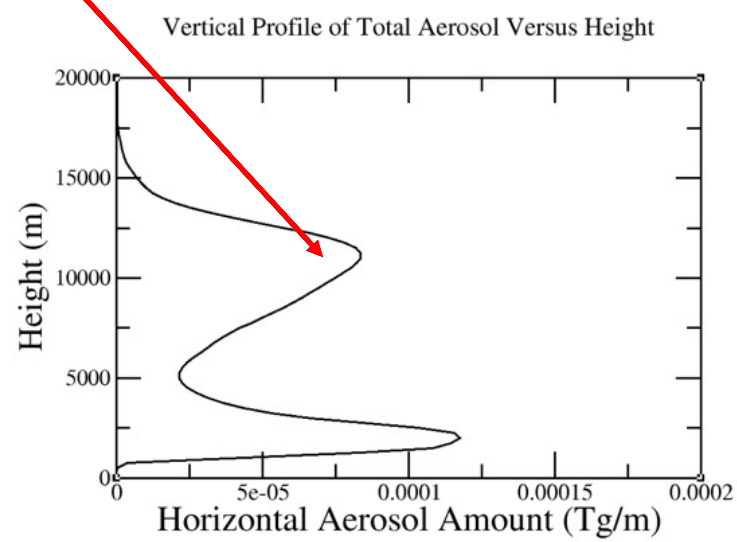
BC17 Modeling Results Compare Well Against Observations (Source)

- Model produces about 0.2 Tg of aerosol at the right height
- Significant fraction is from secondary organic aerosol formation and dust
- Soot content is somewhat higher than observations, 5% (model) versus 3% (observation) of total aerosol content…
- Possibly in line with nuclear winter modeling estimates that also produced too much soot…
  – not representing carbon sinks properly (possible modeling gaps)

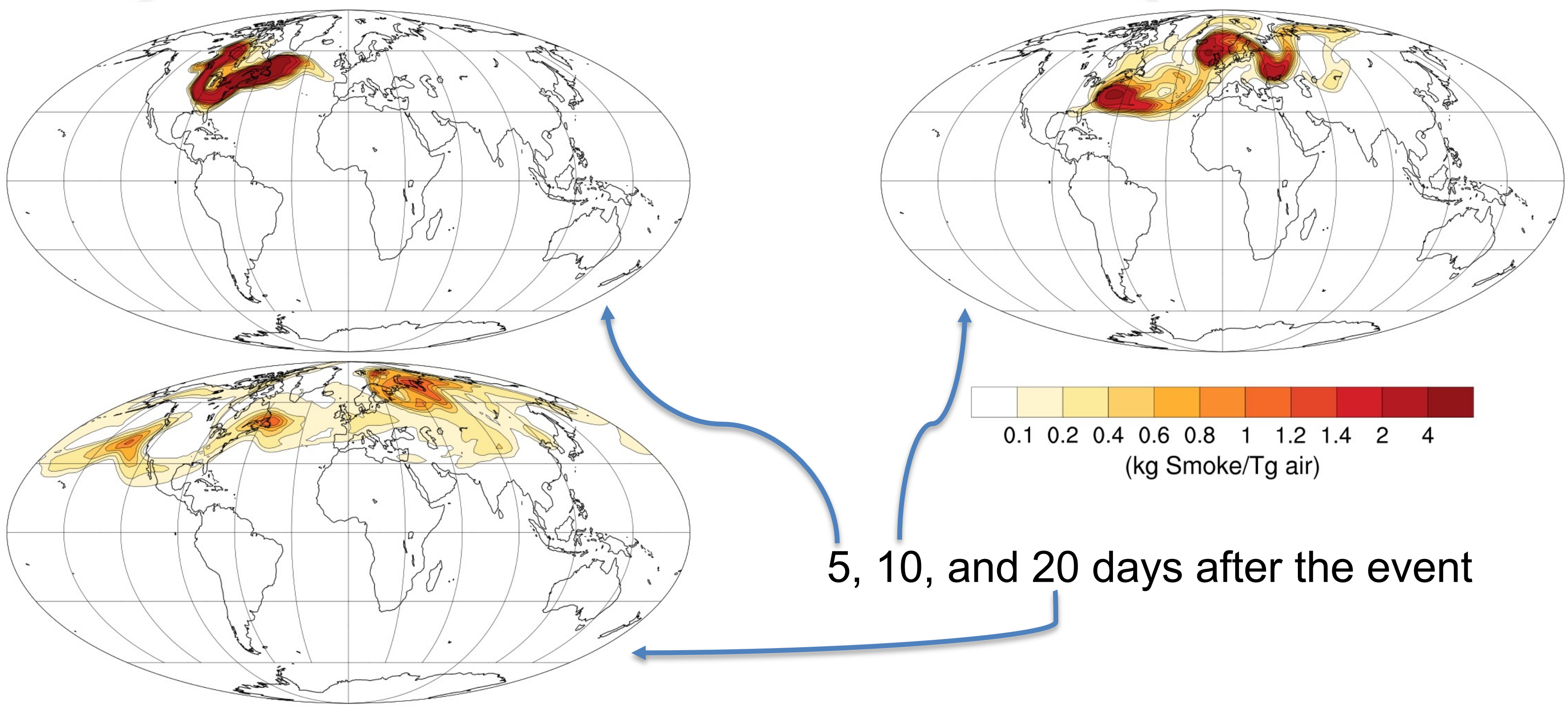
observations



model

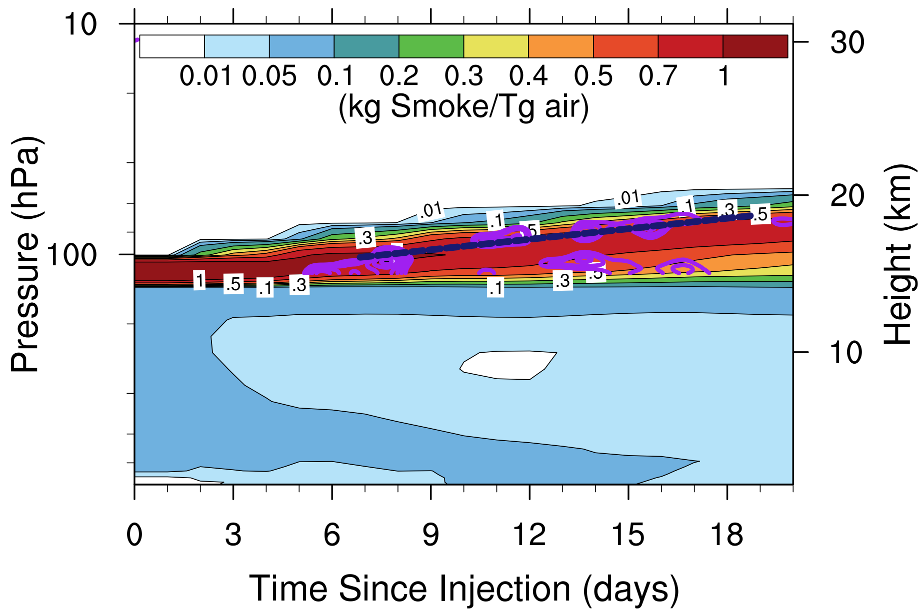


Global Smoke Transport: BC17



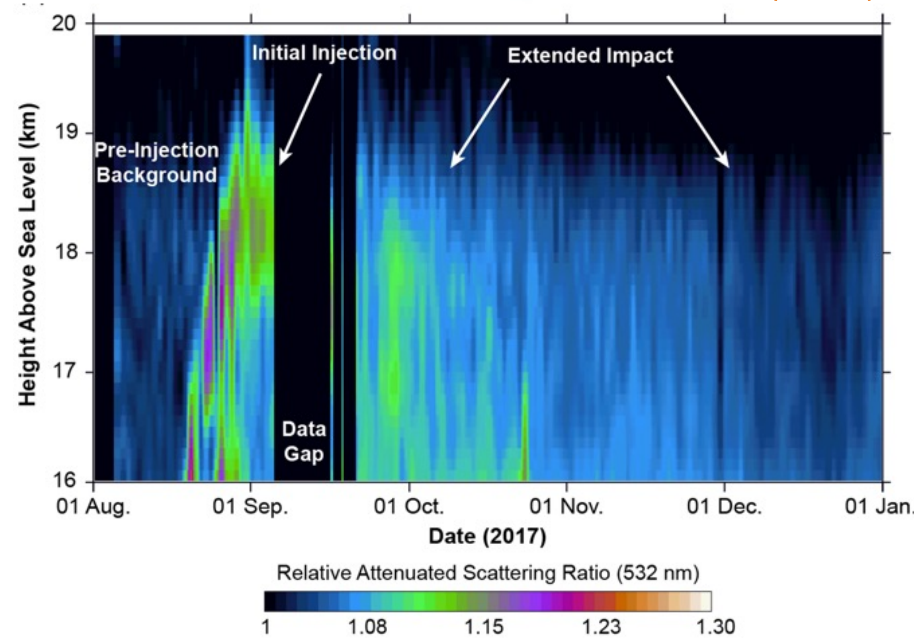
BC17 Modeling Results Compare Well Against Observations (Global Transport)

CESM1 Model Result



Observation

Peterson *et al.* (2018)

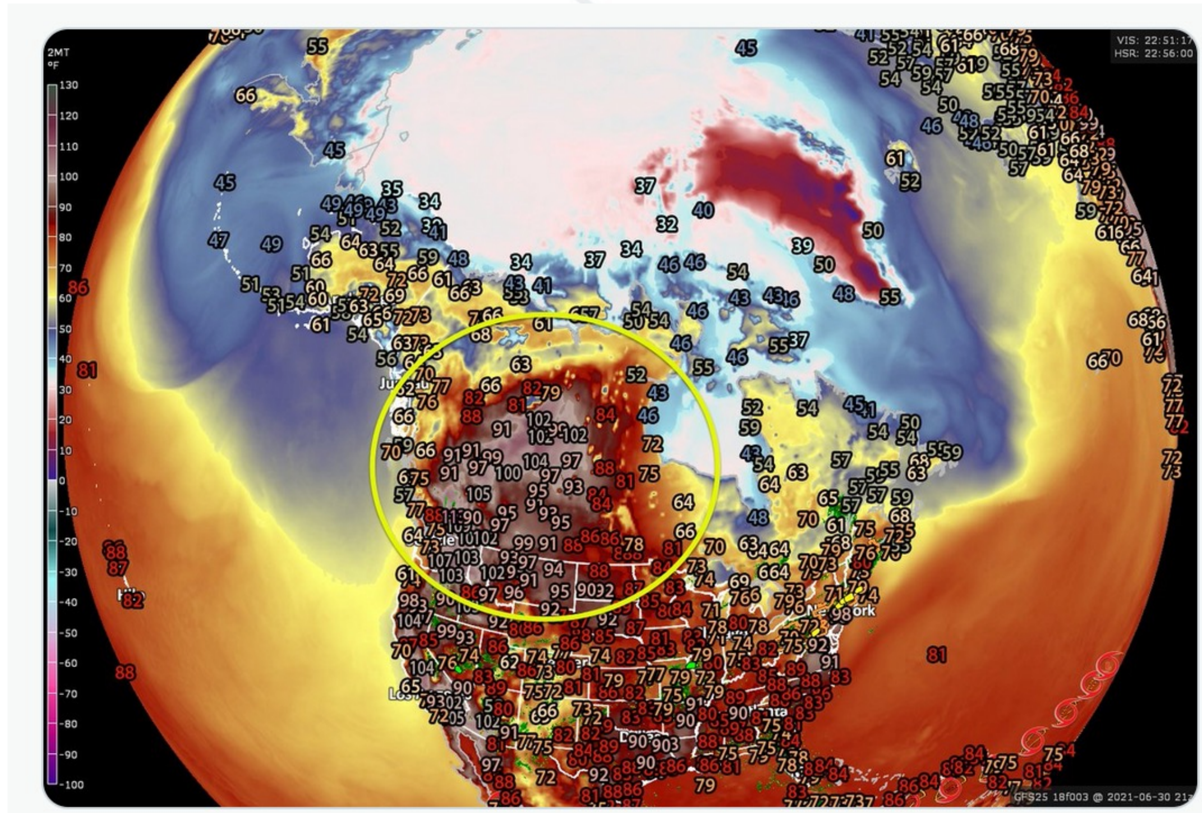


CESM1 model: 0.2 Tg of smoke, 2% BC, injected around 13.5 km

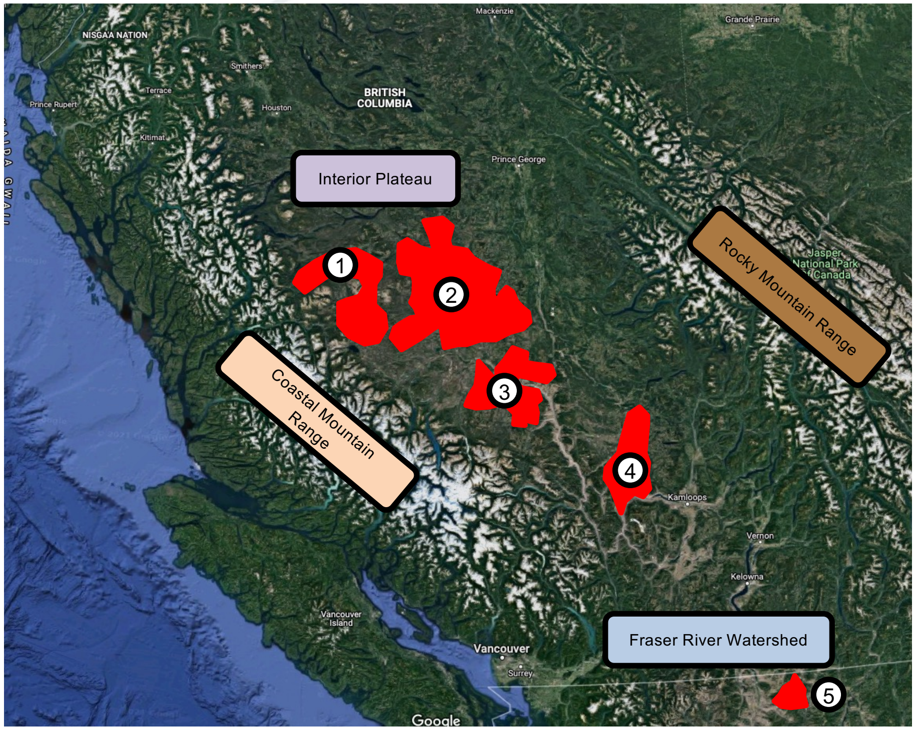
Model matches observed peak plume rise to ~ 20 km

BC21: A Consequence of Climate Change?

- Starting June 26, 2021 a significant heat wave occurred over the Pacific Northwest and Canada
- Temperatures exceeded 100 F over a week and led to rapid drying/death of trees…even in mid latitude rain forests
- Several fires were induced, including the Sparks fire that induced one of the largest pryroCb every observed

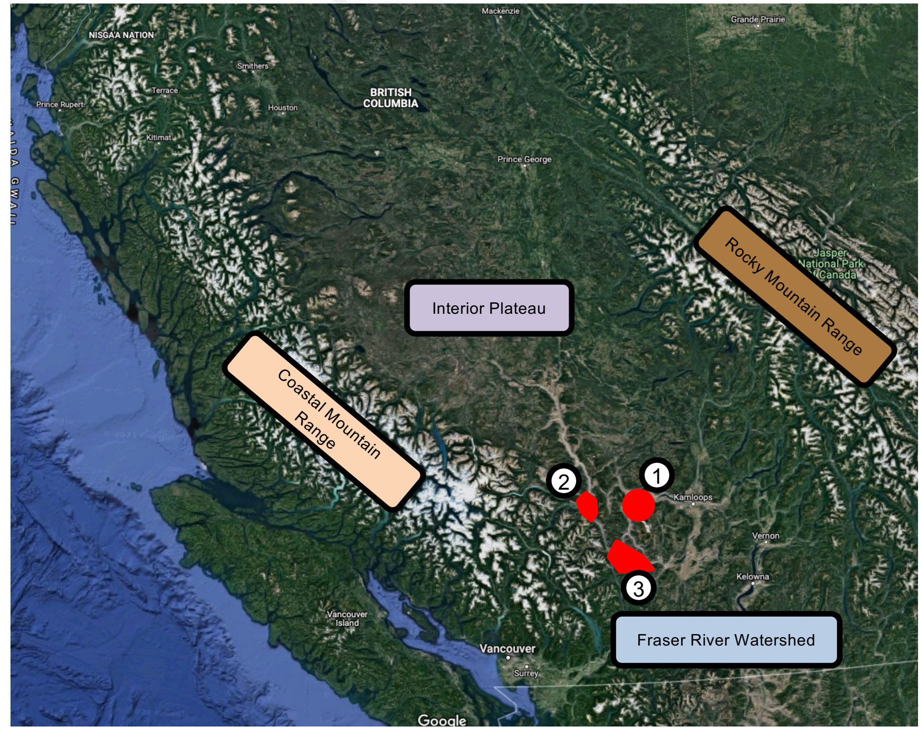


August 12-13, 2017



- 5 observed Pyro-Cb clouds
- Primarily occurring on the interior plateau, a large, flat, and moderate geographic feature spanning the mountains
- Occurred near the end of a record-dry summer
- Swathes of mountain beetle-killed pine contributed to dead fuel loading
- Total burned area largest every recorded by province

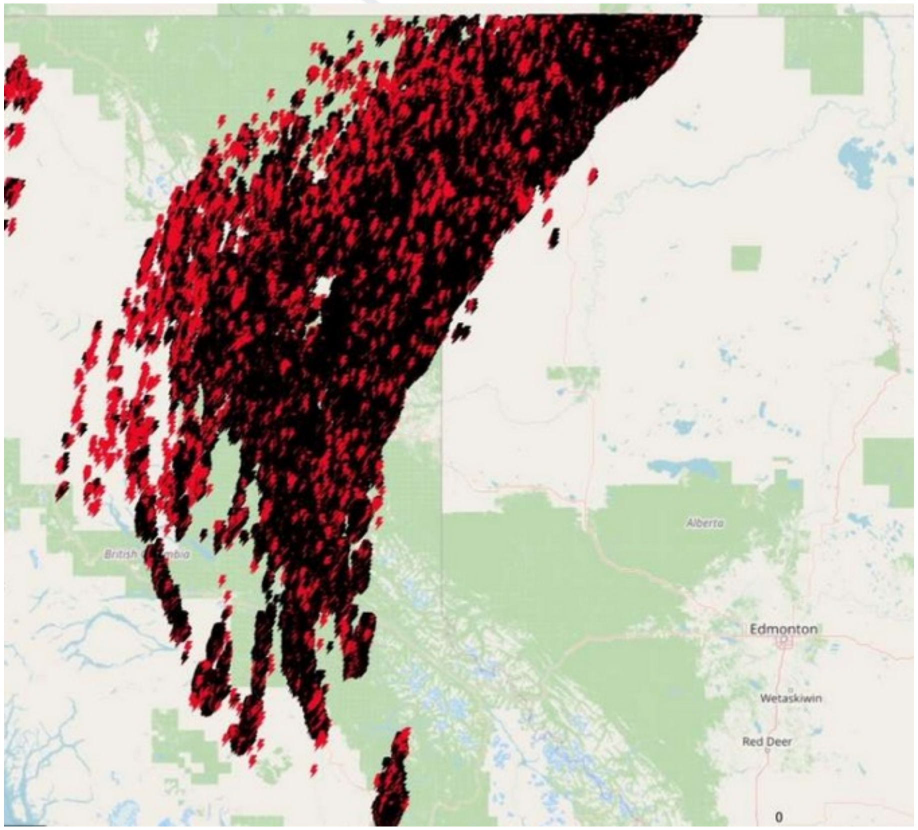
June 30-July 1, 2021



- 2 observed Pyro-Cb clouds (possible 3rd above Lytton)
- Created highest-ever recorded Pyro-Cb (16 km stratospheric injection)
- Occurring in the transition area between the Fraser River Watershed (rain forest) and interior plateau (moderate mountain pine forest)
- Tail-end of week-long record-shattering heat wave

Recent Lightning Strikes from 2021 British Columbia Fire (BC21)

- Average number of lightning strikes during the 1-day time period is roughly 10,000
- BC21 Fire produced 700,000 lightning strikes…
- Or the entire annual number for British Columbia in 1 day
- Temperature in Lytton during the event was 121.28 F (broke 80-year record for the warmest temperature)
- Lightning can start peatlands on fire



Intra-cloud (black dots) and cloud to ground lightning (red dots) July 1 2021

BC21: Understanding Impact of Injection Height and Higher Fuel Loading

- Nuclear winter groups have assumed linear scaling between fuel loading and soot production
- Fuel loading for BC21 was 2.7 g/cm^2 , versus 1.5 g/cm^2 for BC17
- Injection height for Sparks fire within BC21 was 16 km, much higher than 12 km for BC17
- Finished detailed FIRETEC simulations and initial HIGRAD pyroCb simulations
- Currently analyzing global transport of aerosol from satellite data

Fuels

2017

- Forest checkerboarding caused by clear cutting treatments with left slashpiles
- Fuel data sampled from Canadian National Fuel Inventory (2011) northwest of Quesnel provided by Canadian Forest Service
- Dead trees in 'grey' stage, needles/leaves on the ground

Tree Species	Tree Mortality	Fine Fuel Loading	Thick Fuel Loading	Total Fuel Loading
Lodgepole Pine	80%	4.0	9.7	13.7
Doug Fir	40%	2.0	4.8	6.8
Total	**70%**	**6.0**	**14.5**	**20.5**

- Numbers for virgin forest with no slashpiles for comparisons sake

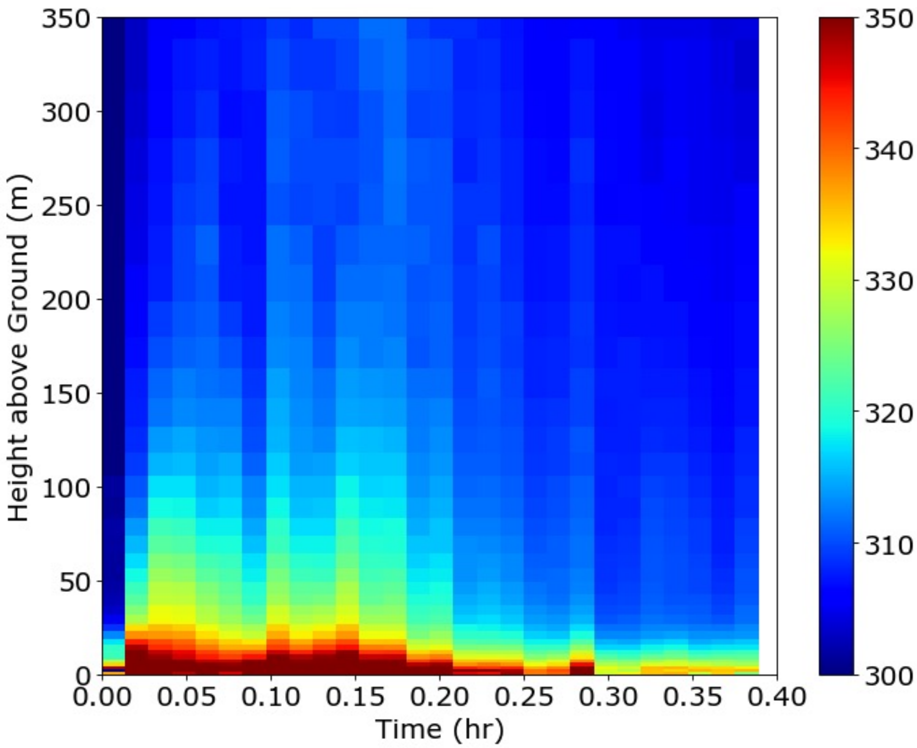
2021

- Mostly untreated forest
- Fuel data sampled from Canadian National Fuel Inventory (2020) within fire perimeter of Cache Creek fire provided by Canadian Forest Service
- Large uncertainties for tree mortality due to heat wave (assumed to be high)
- Dead trees in 'red' stage, needles/leaves on branches but dead
- Under 'normal' circumstances, area is too wet to burn effectively

Tree Species	Tree Mortality	Fine Fuel Loading	Thick Fuel Loading	Total Fuel Loading
Doug Fir	20+20(?)%			
Ponderosa Pine	20+20(?)%			
Total	**40(?)%**	**8.2**	**19.1**	**27.3**

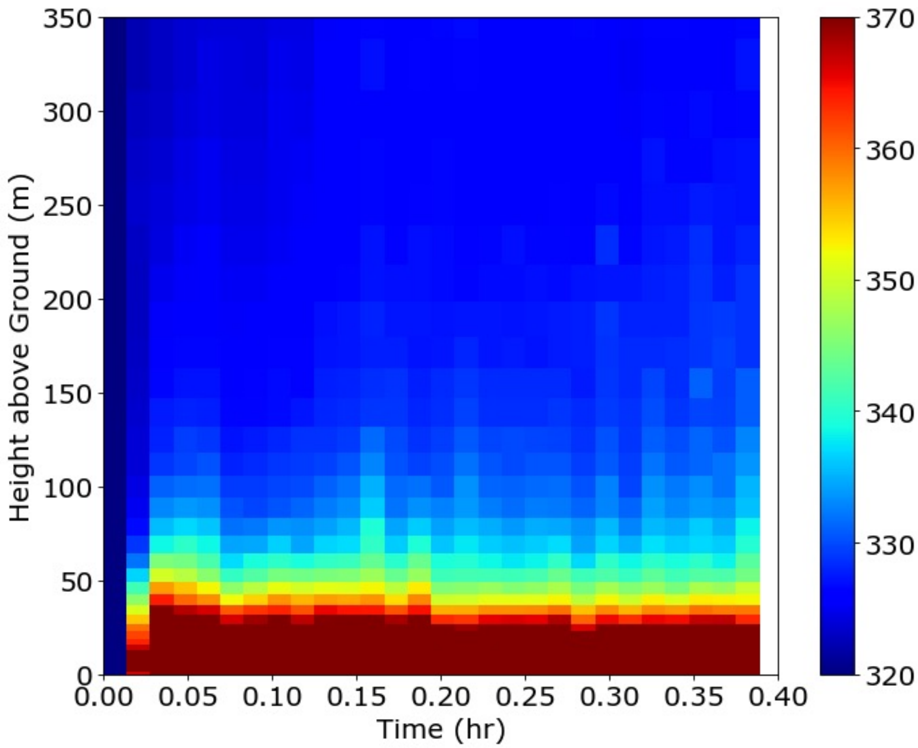
Plume Heat Flux

2017



Peak Temperature = 401 ℃

2021



Peak Temperature = 432 ℃

HIGRAD BC21 PyroCb Simulations: Model Setup

- Forest only simulation (no slash piles)
- Initial focus is the Sparks fire; nearly circular fire that produced large 16 km pyroCb
- Preliminary analysis suggests fire started at a river and then raced up hill (1000 m height change)
- Very hot conditions with light winds (< 5 m/s) throughout the column
- Simple time dependent forcing was specified to mimic a radially moving inward fire
- No ramp up phase, just active fire and smoldering phase

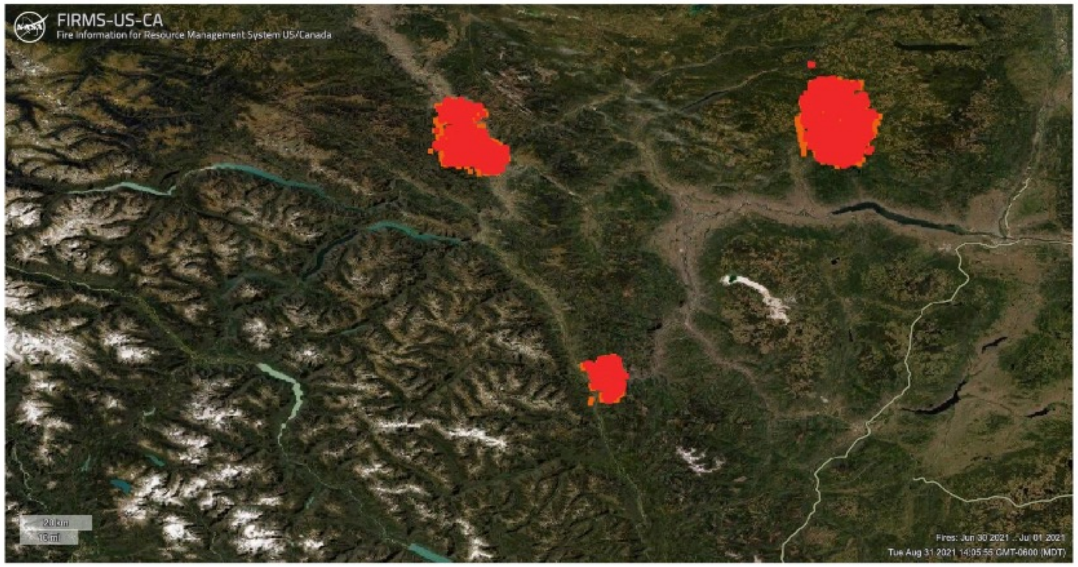
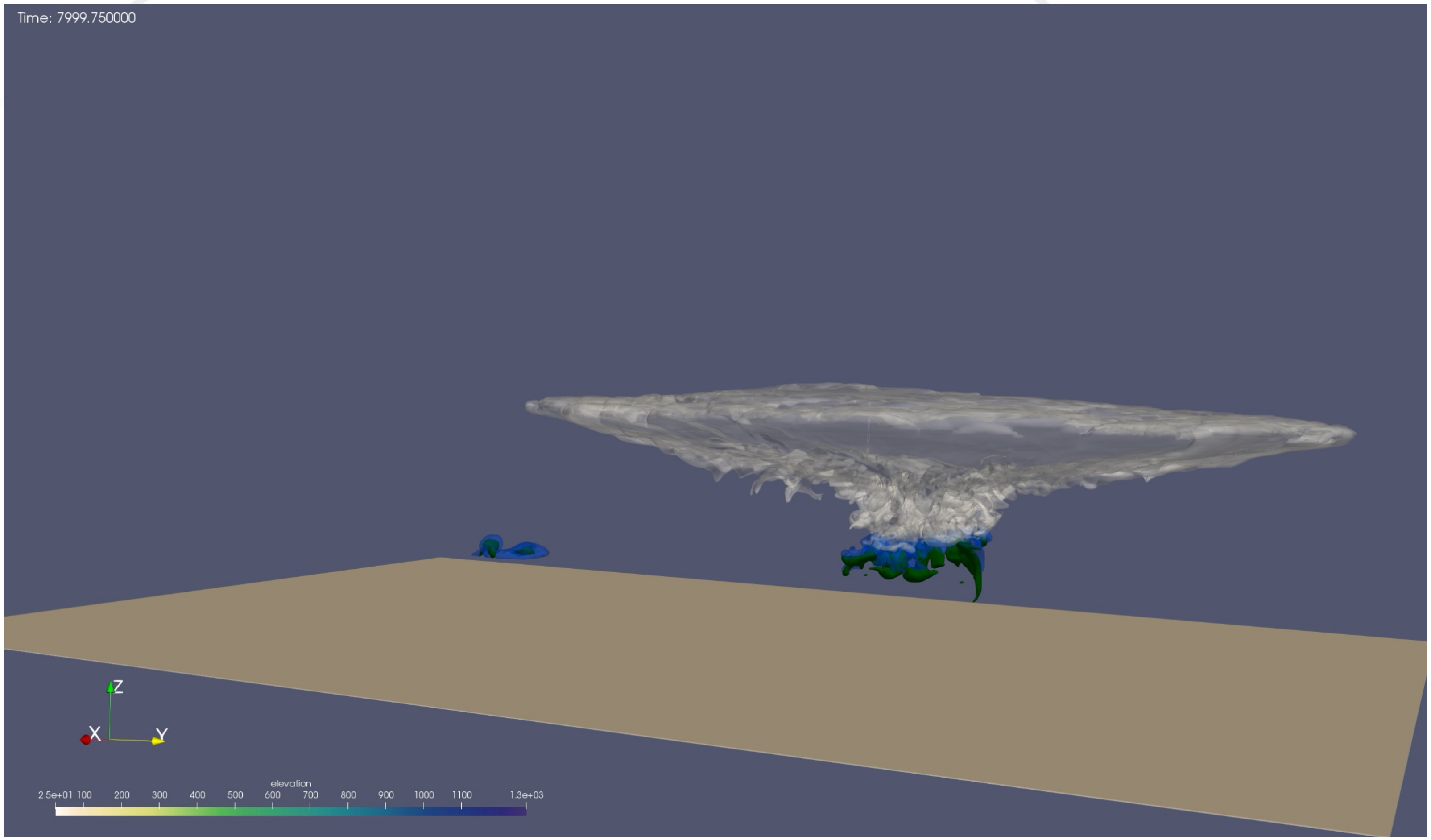
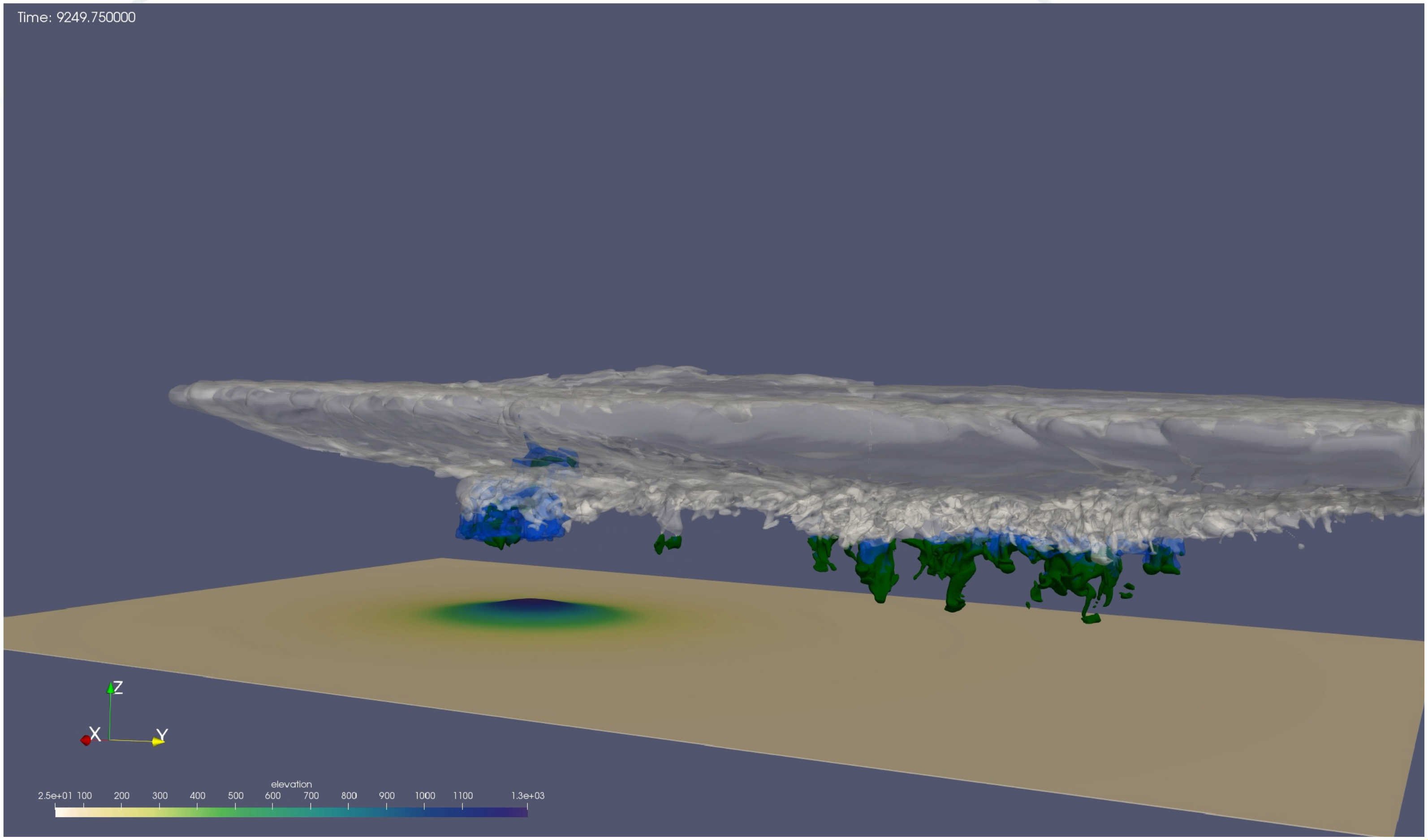


Figure 2: NASA Hotspot Data with a view of McKay Creek Fire (left), Sparks Lake Fire (right) and Lytton Creek Fire (bottom) over 2 days, June 30th-July 1st, 2021.

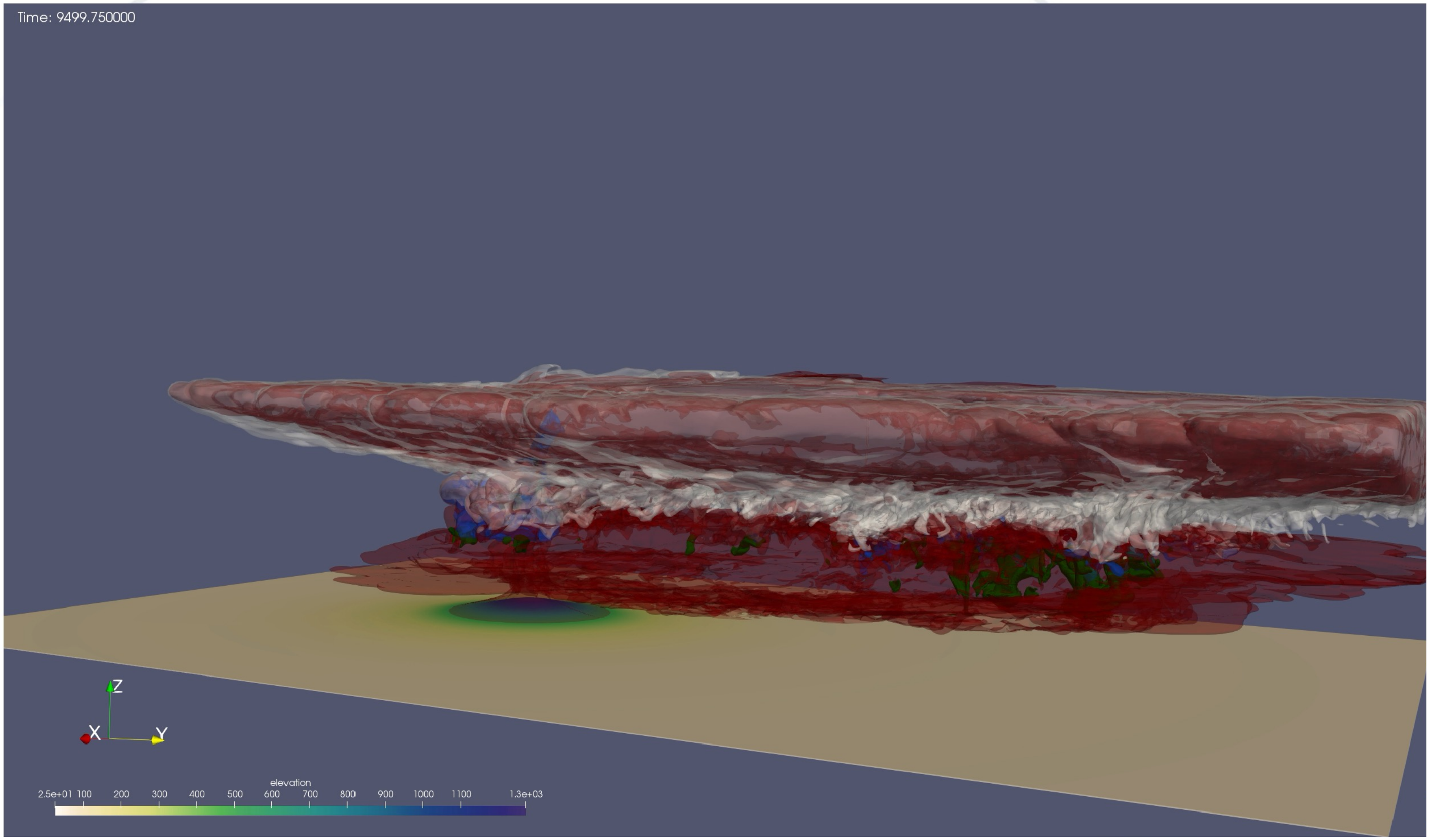
BC21 Simulation: No hill
White (cloud ice), Blue (Cloud water), and Green (rain)



BC21 Simulation: Hill White (cloud ice), Blue (Cloud water), and Green (rain)

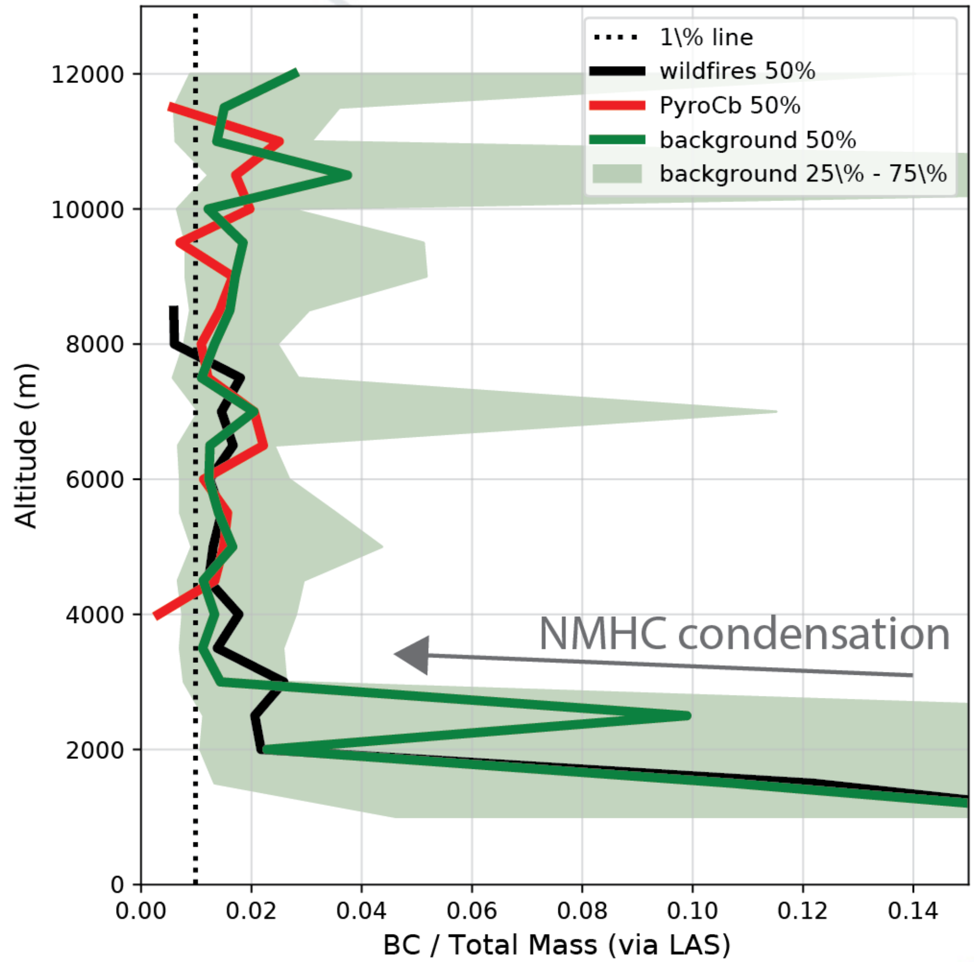


BC21 Simulation: Hill White (cloud ice), Blue (Cloud water), Green (rain), and Organic Aerosol (brown)



Lessons Learned/Questions From BC17 & BC21

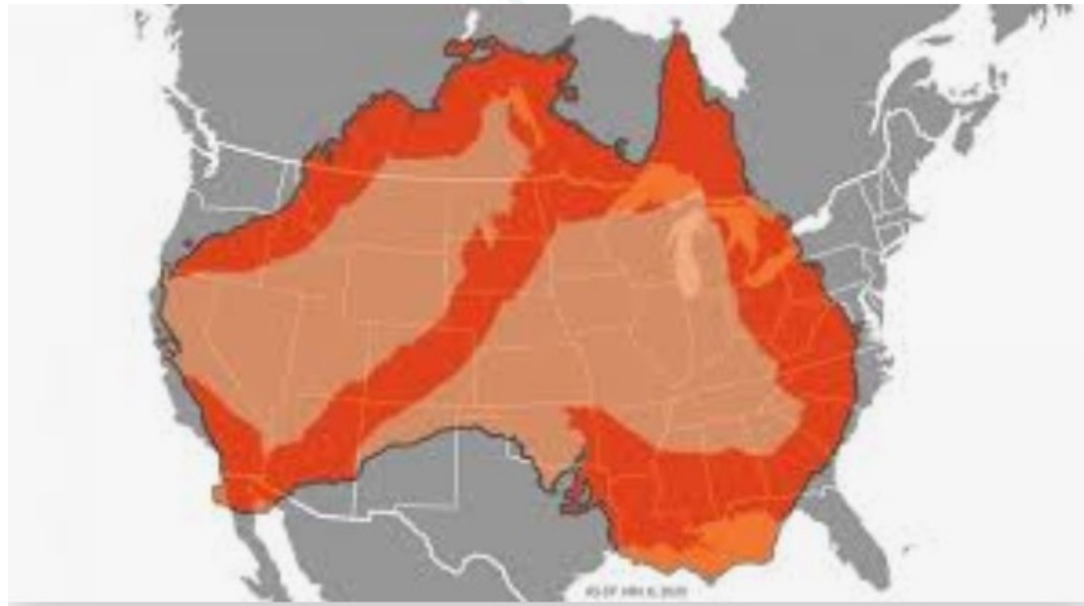
- Preliminary analysis (Peterson) suggests less aerosol injection by BC21 into the stratosphere…but plume still circled the globe
- What was the highest height reached by aerosol plume from BC21?
- Was soot content still at 2%?
- Work with University of Oklahoma to model the lightning
- Do BC17, BC21, and Australian megafires suggest impact of nuclear induced fires was exaggerated?



Can Megafires Be Prevented?

Los Alamos NATIONAL LABORATORY EST. 1943

- National forest services need to work with local agencies/private industry to thin forests & remove slash piles
- CO_2 levels need to be mitigated
- Drones and other observing platforms need to quickly identify fire starts & coordinate with firefighting resources
- Don't' plant trees that burn like gasoline, e.g., eucalyptus



Areas burnt in red in 2020